CBRS Infrastructure and Devices 2019

Abstract: This report provides a comprehensive review of the CBRS ecosystem to assess its potential growth, market size, and timing. Infrastructure, SAS connectivity, and core network issues are balanced with the handset, CPE, and IoT device availability. Key applications driving the market including fixed wireless, mobility, and private LTE use cases are investigated to fully assess the potential of the CBRS market for mobile operators, cable operators, wireless ISPs, neutral hosts, and enterprises.

Kyung Mun

December 2019

MOBILE EXPERTS

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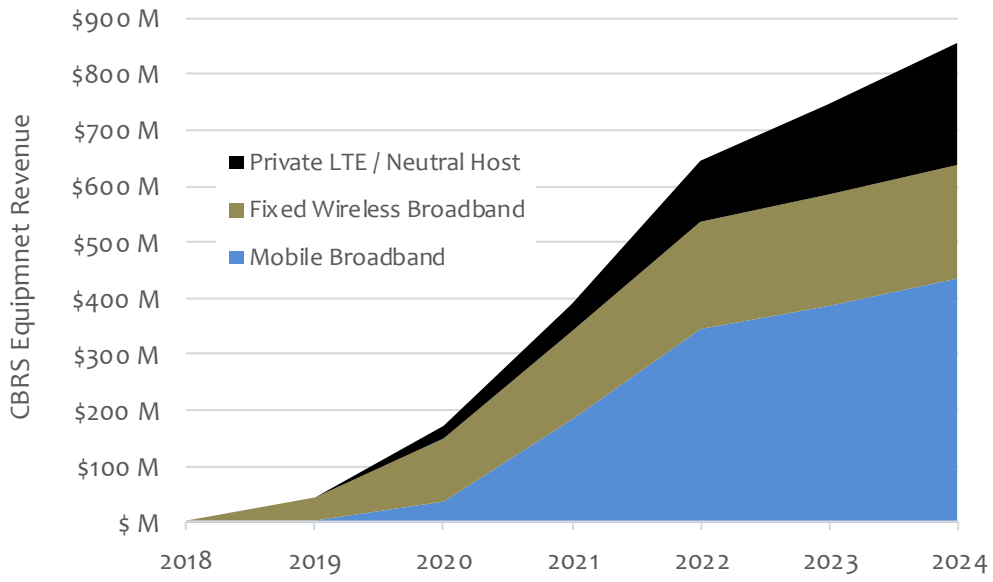
1 EXECUTIVE SUMMARY

Full commercialization of the CBRS spectrum has been delayed for the equipment manufacturers and solution providers, but some major progress has been made during 2019. Mobile Experts had expected that the revised FCC rulings published in late 2018 on the CBRS licensing terms, including county-based coverage areas and a ten-year term duration would have provided clarity and the full commercialization to have started during the second half of 2019. Based on a busy schedule of topics[1] at the FCC during the past year, perhaps the industry should celebrate the accomplishments and milestones reached, including:

- Initial Commercial Deployment (ICD) launch in September 2019;
- 150 member companies in the CBRS Alliance;
- 5 approved SAS providers;
- 20+ FCC-approved CBSD infrastructure products;
- 50+ FCC-approved end user devices; and,
- PAL spectrum auction (Auction 105) scheduled for June 25, 2020.

Both operator- and enterprise-driven applications and use cases are driving the CBRS/OnGo market activities. Fixed wireless deployment leveraging the new CBRS spectrum by major operators like AT&T and local Wireless ISPs is a clear near-term opportunity. Network capacity expansion through carrier aggregation of CBRS small cell layer is another key motivation for mobile operators, especially Verizon which is somewhat "spectrum-starved" relative to peers. Meanwhile, mobile offload is a key driver for cable operators who are looking to reduce their MVNO costs by directing mobile subscriber traffic to own CBRS network. Finally, enterprise-driven private LTE use cases such as connecting video surveillance cameras, IoT sensors, and other mission-critical applications are driving adoption at key venues. As CBRS-ready smartphones reach a meaningful penetration of the installed base (during 2022-2023), we expect to see the neutral host in-building cellular application further driving the market.

[1] Major issues kept the FCC busy during 2018-2019, including: the T-Mobile/Sprint merger, millimeter wave spectrum auctions, the C-band (private vs. public) auction plan, CAF-II auction, and on-going coordination with NTIA and DoD to open up the CBRS band.



* Note: revenue excludes CBRS-capable smartphone sales

Source: Mobile Experts

Chart 1: CBRS Infrastructure and Device Revenue Forecast, 2018-2024

The near-term CBRS equipment market will be driven by fixed wireless and private LTE use cases, to a lesser degree. The transition of old Part 90 systems to Part 96 (CBRS) will provide an immediate opportunity as the old incumbent fixed wireless systems operating in the 3.65 GHz band will need to migrate over to Part 96 by the April 2020 deadline. The CBRS equipment market, including small cell infrastructure and end devices, excluding smartphones, will grow from less than $50M in 2019 to over $850M in 2024. The mobility application will drive over 50% of this market in 2024, followed by private LTE and neutral host applications (26%) and fixed wireless (24%). This market growth represents over 270,000 indoor and outdoor small cells authorized to operate in the CBRS band, about 600,000 fixed wireless broadband CPE devices, and 700,000 IoT devices such as mobile router/gateways, modules, etc. in 2024.

In terms of capital expenditure of CBRS infrastructure and devices excluding smartphones by group, the mobile operators will be the biggest spender on CBRS equipment, purchasing over $1.1B cumulatively over the next five years (2020-2024). The cable operators will be the next biggest spender at $740M of cumulative spend. The enterprises and neutral hosts will spend at $560M of cumulative spend over the next five years. Lastly, the WISPs will spend over $380M cumulatively over the next five years.

2 MARKET UPDATE

During the past year, the CBRS ecosystem made good progress towards commercialization. The Initial Commercial Deployment (ICD) launch event in September of this year was a significant milestone for the industry as it signaled that full commercialization was near. The FCC certified major SAS systems in concert with the ICD launch, and the crucial ESC sensor networks are close to completion by the end of 2019. The CBRS Alliance now boasts 150 member companies, including all major mobile and cable operators, tier-1 and upstart equipment manufacturers, system integrators, and enterprise-focused solution providers. Despite the progress made, the commercial market for CBRS equipment and software solutions has been slow to materialize.

While the underlying market drivers and use cases for the new CBRS spectrum haven't changed much, the pace of CBRS investment decisions among key stakeholders has fluctuated during the past year. Mobile Experts believes that this is mainly due to key external factors such as C-band (3.7 – 4.2 GHz) auction timing and T-Mobile/Sprint merger that will meaningfully impact the industry at large. While we believe CBRS has a growing role in both carrier and enterprise deployment of mobile infrastructure and devices, it is a small piece in a larger puzzle piece that represents the dynamic U.S. wireless industry.

Market Drivers and Applications

The innovative spectrum rules around different tiers of access, relatively smaller license sizes, etc. make the CBRS band appealing to a broad array of players ranging from enterprises, small wireless ISPs, and major operators. Some of the key use cases and business models driving the CBRS ecosystem are:

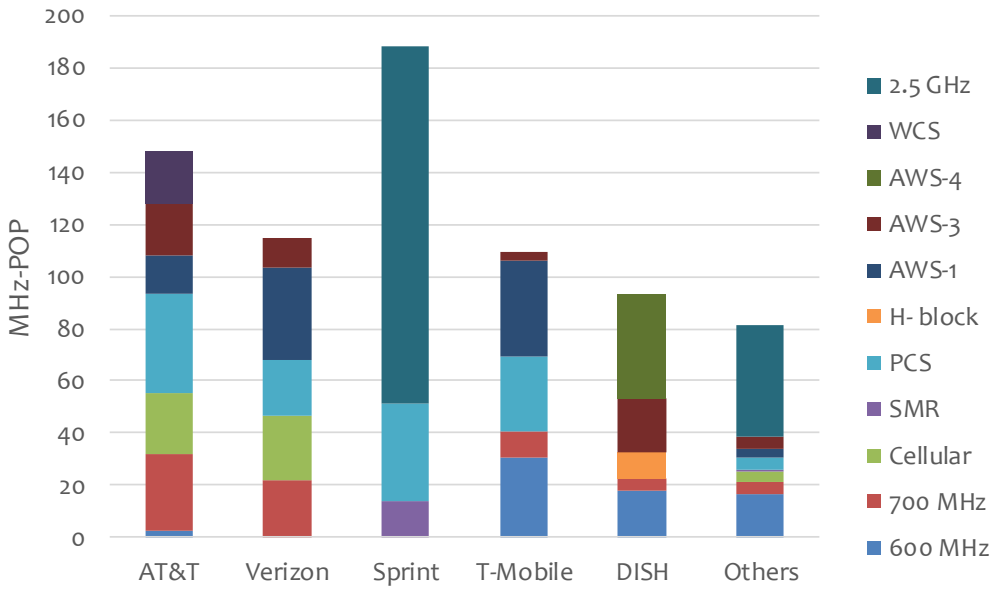
1. Fixed Wireless Access: One of the simpler use cases for CBRS involves outdoor infrastructure and fixed broadband service for residential and enterprise customers. For simplicity, we focus on the residential broadband case in this report.
2. Private LTE Networks: Enterprises can implement their private wireless networks as a way to enhance security, to create IoT connectivity for operational efficiency, or to save money by forgoing public cellular services.
3. Neutral Host Access: A neutral host provider can implement a CBRS network as a neutral in-building wireless system instead of aggregating myriad licensed carriers through a DAS system, for example.
4. MNO Capacity Augmentation: Mobile operators can increase network capacity by aggregating data channels on the CBRS band with a signaling channel on a licensed carrier.
5. MVNO Mobile Offload: Cable operators can alleviate expensive "rent" costs associated with data support by mobile competitors, by offloading mobile traffic onto their small cell network, leveraging CBRS spectrum.

While we have observed continued progress in each of the key use cases highlighted above, the "Fixed wireless access" and "Private LTE" segments have been most active up to this point. In terms of the market opportunity for CBRS equipment manufacturers, Mobile Experts believes the "MNO capacity augmentation" and "MVNO mobile offload" applications, i.e., the key use cases for the major mobile and cable operators, will drive the market.

Mobile Operators

With higher power limits, the mobile operators will use CBRS spectrum in a manner that's similar to LAA (using 5 GHz unlicensed spectrum). That is, the mobile operators will use their licensed spectrum as a primary carrier and multiple 10MHz CBRS bands as secondary carriers in a carrier aggregation mode. Instead of a much smaller LAA footprint (~50-100 meters in NLOS reach), CBRS small cells will offer a larger cell coverage (~300-400 meters). The mobile operators' CBRS use will be like "LAA on steroids" with much bigger footprints for the CBRS data capacity layer.

Although all four major mobile operators are members of the CBRS Alliance, the level of interest in CBRS infrastructure deployment differs among the mobile operators. Not surprisingly, a key driver of individual operators' interest, or lack thereof, is driven largely by their spectrum holdings and how urgent their spectrum needs are.



Source: FCC, Mobile Experts

Figure 1. U.S. Mobile Operator (Sub-3GHz) Licensed Spectrum Holdings

Verizon has been most active and vocal about its planned use of the CBRS band for adding capacity to its network. As shown above, it is not surprising to see why. Verizon and T-Mobile have the least amount of low and mid spectrum (i.e., those below 3 GHz) among the four major operators. In terms of licensed spectrum holding per subscriber, Verizon's spectrum position is even worse as it has the largest base of mobile subscribers. As of the third quarter of 2019, Verizon reported close to 120M subscriber connections. In other words, Verizon has been very efficient in spectrum utilization, and it looks to continue that streak through applying low-cost CBRS spectrum options. Based on Ericsson's and Nokia's CBRS outdoor small cell products that have been authorized some months back, we estimate that Verizon has already deployed thousands of CBRS-capable small cells in urban hotspots and will be bringing these units online once the FCC authorizes full commercialization through approving ICD test reports.

AT&T has also been active in the CBRS ecosystem and has announced its plan to leverage the CBRS spectrum to expand its fixed wireless network across 11 states. It plans to deploy massive MIMO (64T64R) base stations along with high-power CBSD Category B devices as subscriber CPE units to maximize coverage and data throughput in the mostly rural environment. AT&T's plan for mobility use of the spectrum is not clear at this point. Mobile Experts believe that AT&T will possibly use CBRS along with its LAA deployment on the unlicensed 5 GHz band as a part of its "5G evolution" expansion. Since the physical nature of the 3.5 GHz CBRS band propagating further out than 5 GHz LAA, it is possible to see CBRS replacing LAA small cells in future 5G evolution rollouts into suburban markets.

With the pending merger in a final "stretch" with a possible court battle with several States next month, T-Mobile and Sprint have not been very active. While we believe T-Mobile and Sprint may conduct lab trials to understand the characteristics of CBRS small cells on its overall network performance, it is not likely that they will be serious about deploying CBRS for mobile use in the near term. If the planned merger somehow falls apart through State win in court litigation in December, we believe T-Mobile may become more active in leveraging CBRS in its "mid-band" plan. However, we believe this is less likely at this point.

Cable Operators

Major cable operators in the US are making their way into the mobile market via the MVNO arrangement that they struck with Verizon as a part of their AWS spectrum sale back in 2011. As of the third quarter 2019, the cable operators reported a combined total of 2.6M mobile subscribers.[2] In context of over 300M mobile subscribers in the U.S., the cable operators' share is tiny. Nonetheless, cable operators are slowly growing their wireless businesses. While they would certainly like to grow their wireless businesses quicker, this is a long game

[2] Comcast reported 1.8M wireless subscribers, and Charter reported about 800k subscribers. Altice reported 15k subscribers for a short timeframe during the third quarter when it launched its wireless service through a Sprint MVNO.

for them in the context of larger fixed-mobile convergence and competition as subscriber behaviors change.
The mobile and cable operators are beginning to compete more directly as each side gradually fights to retain subscribers that they already have on their core services -- i.e., fixed broadband and video for the cable operators and wireless for the mobile operators. The major cable operators now compete for mobile subscribers, and the mobile operators are increasingly posturing towards fixed wireless service offerings (e.g., Verizon's 5G Home fixed wireless service).

A big question for the cable operators is how best to scale their wireless business. As an MVNO "renter" of host provider's RAN network, the profitability of its mobile business depends mostly on how much it can directly serve its mobile subscriber traffic. While the cable operators boast about tens of millions of Wi-Fi hotspots to offload traffic, they don't have complete control over how traffic is diverted, and more importantly, the impact on user experience as mobile device roams across LTE and Wi-Fi networks. With CBRS small cells, the network integration and service continuity across the host operator's LTE macro and owned CBRS small cells may afford more seamless user experience than "brute" method of offloading to Wi-Fi. A few percentage drops in mobile traffic going over the Verizon network could mean profitability vs. loss for a cable MVNO (depending on an MVNO agreement, of course).

The best solution is a facilities-based mobile strategy where mobile traffic is passed through owned network so that the variable cost, or "rent fees" to a host mobile operator, can be minimized or altogether eliminated. With a potential deployment of CBRS small cells on strand-mount and DOCSIS as backhaul, the cable operators can stand up cost-effective mobile offload network. Charter has been very active in CBRS field trials over the past couple of years, and field trials appear to show the viability of this solution. However, its intention to use CBRS small cells as mobile off-ramp to the Verizon host network has been somewhat on a "holding pattern" as of late. We believe this is mainly due to a commercial arrangement it needs to have in place with Verizon to direct traffic away from Verizon's mobile network onto Charter's owned network. For a successful facilities-based strategy, the cable operators need to have own Core EPC network so that it can provision its own SIM cards and put in policy to direct mobile traffic from host network(s) to an owned network.

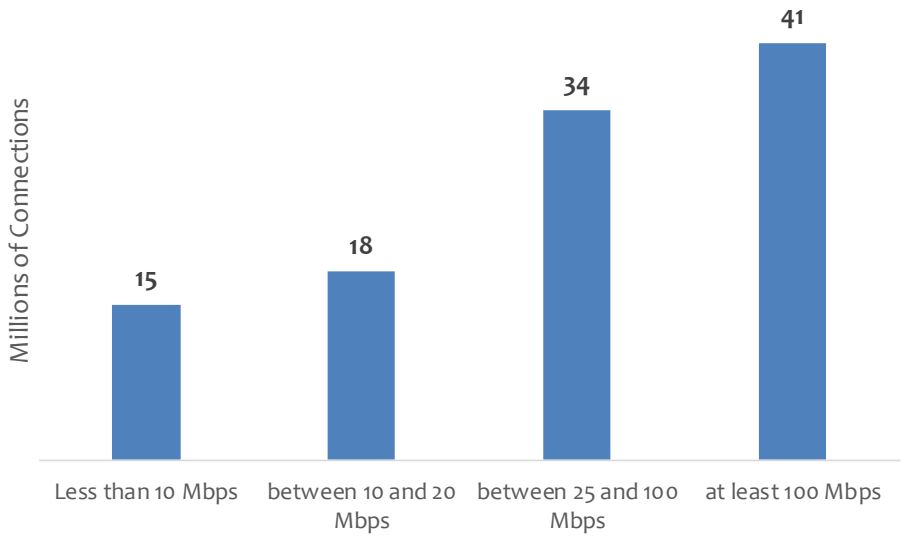
The two largest cable operators, Charter and Comcast, are actively working on mobile Core EPC development through a 50-50 joint venture that they officially announced back in April 2018.[3] Mobile Experts believes that the cable operators will first harden its Core EPC and IMS infrastructure before seriously ramping up its CBRS small cell deployment. Having its Core EPC integrated with IMS infrastructure provides tremendous flexibility and leverage during MVNO negotiations as the cable operators can easily migrate its mobile subscriber base onto another host MVNO network.

[3] https://www.multichannel.com/news/comcast-charter-form-mobile-platform-partnership

Altice USA has a separate MVNO agreement with Sprint and has just launched its mobile service with pretty aggressive pricing ($20 per month). It is believed that Altice has its Core EPC and will transition its "infrastructure-sharing" MVNO agreement with Sprint onto the New T-Mobile once the merger goes through. Altice's MVNO agreement with Sprint involves Altice deploying small cells on behalf of Sprint, who pays the CAPEX for those small cell installations. As a part of the agreement, the two companies effectively share the small cell network capacity, and Altice can negotiate a very aggressive MVNO rate in place of providing site lease on its cable strands and backhaul via DOCSIS cable network.

Fixed Wireless Operators

While operators continue to invest in network infrastructure, the number of homes and businesses that get inadequate broadband connections still looms large. According to a recent FCC report, over 15 million Americans still rely on broadband speeds less than 10 Mbps downlink as of December 2017, because they can't get decent broadband services to their homes.[4] Considering the FCC's new definition of 25/3 Mbps (downlink/uplink) as "broadband" speed, there are 32M households and businesses that are lacking "broadband." Assuming an average revenue opportunity of $50/month, this represents a $19B broadband service revenue opportunity that is still unmet due to the high cost of passing rural and suburban homes with copper, coax, or fiber.



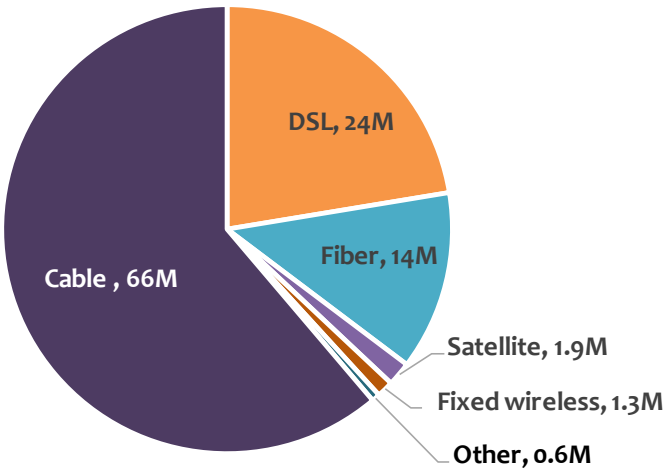
Source: FCC, Mobile Experts

Figure 2. U.S. Broadband Connections by Downlink Speed Tiers

While large portions of American homes and businesses are connected through capable broadband technologies such as fiber and cable, there is still a large segment of the broadband market dominated by low-speed technology alternatives such as DSL and satellite. With the potential of leveraging low-cost CBRS spectrum options, fixed wireless

[4] FCC Internet Access Service report, as of December 31, 2017 (August 2019)

can offer broadband-speed offerings in the range of 25/3 and 100/10 Mbps services, especially in rural markets where spectrum-sharing concept is generally accepted and sometimes, the only option for wireless ISPs (WISPs) that generally serve these underserved markets.



Source: FCC, Mobile Experts

Figure 3. Technology Mix of the U.S. Broadband Connections, as of Dec. 2017

The spectrum sharing concept envisioned in CBRS works much better than the traditional exclusive licenses for rural fixed wireless applications. In rural areas, a local entrepreneur can set up a CBRS network based on fiber or wireless backhaul to a central location, with several subscribers sharing each CBRS access point. The opportunistic use of the CBRS spectrum under GAA may be just fine for entrepreneurial WISPs where the possible contention for the CBRS spectrum can be managed or coordinated through SAS, unlike the current operations using the 5GHz unlicensed spectrum where there is no central coordinating body or database.

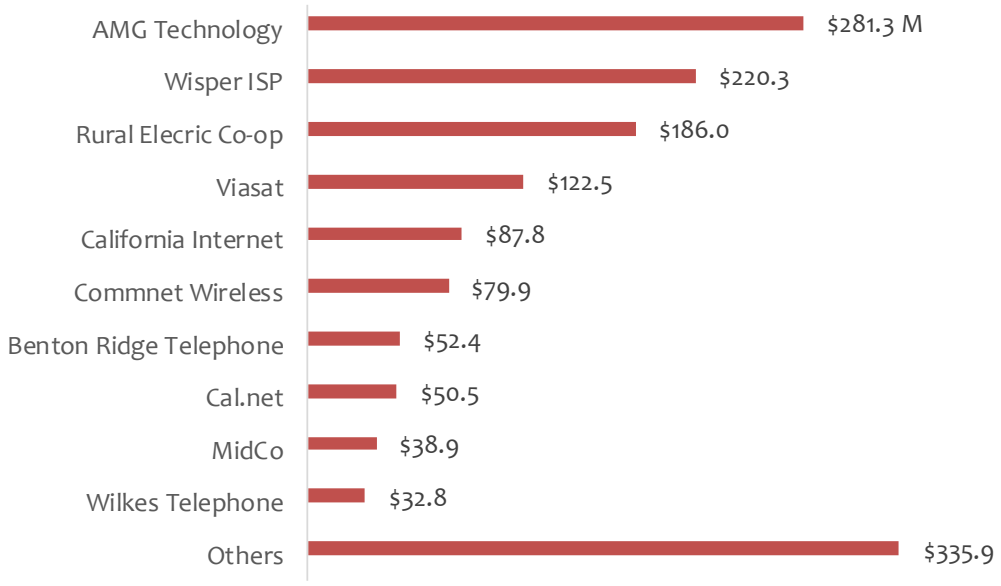
While rural customers are often targeted for fixed wireless service, they are not the only opportunity here. Many urban and suburban customers in the U.S. are stuck with only a single choice for viable broadband service offerings. With superior hybrid-fiber-coaxial (HFC) plants, cable operators have been taking share away from telcos' copper-based DSL offerings for some time. While some telcos are expanding their fiber footprint, the availability of high-speed broadband offerings through fiber has been less than cable broadband offerings. With one or two competitive offerings in most markets, the pent-up demand for alternative broadband services is strong but fragmented. Vivint is one such operator looking to extend its Internet service footprint through fixed wireless. It has a couple of markets and is working on launching its "2.0" version using latest technologies based on CBRS and other spectrum opportunities. Its plans will depend on whether its spin-

off and financing plans from its core parent company, which specializes in home security and smart home offerings.

The fixed wireless opportunity can vary by region and is not well suited to a "one-size-fits-all" solution. Until major operators divert significant capital toward the fixed wireless market opportunity, it will likely be addressed through hundreds and even thousands of entrepreneurial local and regional companies in unserved or underserved markets. Many WISPs are constantly on the lookout for new spectrum opportunities, and CBRS has certainly piqued their interest. The immediate CBRS opportunity will be transitioning about 10,000-12,000 fixed wireless access points operating under the legacy Part 90 rules to CBRS Part 96. While many of the legacy infrastructures may be converted through grant authorization, some will need to be replaced altogether. In addition to the access points, a portion of 80,000 – 100,000 legacy Part 90 subscriber units may need to be replaced as well.

A major market driver for fixed wireless operators is the government's on-going effort to broaden faster Internet connectivity to rural markets. The FCC's Connect America Fund Phase II (CAF-II) program will help drive capital investment into this space. As expected, both large and small companies were active in bidding for the CAF-II funding. Based on the CAF-II auction results[5], which will pay out about $1.5B of government funding to the winners, both large and small players won the funding support. Mobile Experts believes that a large share of this funding will go towards fixed wireless network deployments.

[5] FCC CAF-II auction results, https://docs.fcc.gov/public/attachments/DA-18-887A2.pdf



Source: FCC, Mobile Experts

Figure 4. CAF-II Funding Winners

According to the FCC, all but 0.25% of over 713,000 locations assigned will have 25/3 Mbps broadband connectivity. Many of the CAF-II winners are WISPs who mostly serve rural areas.

Enterprise and Neutral Host Providers

With a possibility of the low-cost spectrum "ownership" through PAL licensing, non-carrier players like enterprises, neutral-host providers, and even some system integrators are contemplating CBRS infrastructure and devices to meet more stringent requirements of mission-critical applications found in some enterprises and venues. Generally, industrial enterprises and venues have stringent requirements on their private wireless networks. While Wi-Fi is sufficient for the general broadband connectivity needs of enterprise workers, it is harder to provide reliable deterministic links especially when some mobility is required. For example, in a large shipping ports or oil & gas mining fields, providing a wide coverage may require 100's of Wi-Fi access points and managing reliable data links among that many access points can be problematic due to contention between access points and end user devices. Rogue Wi-Fi hotspots have been a problem for many enterprises attempting this kind of Wi-Fi deployment. With private LTE infrastructure using the CBRS spectrum, fewer access points would be required, and mobility aspects can be more easily managed.

As industrial enterprises increasingly rely on broadband connectivity and leverage more IoT sensors for data gathering and automation, an opportunity for private LTE-based

communications networks is starting to diversify and grow. While most enterprises have largely relied upon Wi-Fi for wireless network services, there is a growing recognition that private LTE networks are desirable in use cases where reliable, secure, and predictable connectivity across large geographic footprints, especially outdoors, is needed. Over the past year, several private LTE trials and commercial deployments were announced:

- Landmark Dividend / Dallas Area Rapid Transit (DART): Landmark Dividend is a real estate company specializing in ground lease acquisitions. In other words, it secures rights to real estate properties and creates value-add services. One of the value-added services that the company took was creating a private LTE network using CBRS spectrum to connect hundreds of digital signages along DART rail system in the Dallas metroplex. It sees opportunities in other verticals and working to establish private LTE systems at key venues.

- Times Square in NYC: Connectivity Wireless Solution is a 10-year old system integrator providing in-building coverage solutions to operators and industry verticals. Connectivity partnered with Commscope/Ruckus (for access points), Federated Wireless (for SAS), Athonet (for Core EPC), and Sky Connect Networks for an ICD trial to multiple private LTE applications including video camera, public safety push-to-talk, voice and video calls on smartphones, digital signage connectivity, and backhauling Wi-Fi access point traffic.

- Angels Stadium: Connectivity Wireless Solution in partnership with JMA Wireless (for XRAN virtualized baseband and CellHub radio units), Athonet (for Core EPC), and Federated Wireless (for SAS) deployed a private LTE network for backend support operations including retail point-of-sale systems, ticketing, digital signage, and secure internal communications.

- American Dream Mall in East Rutherford, NJ: American Dream is an entertainment complex located near the MetLife Stadium. It has over 4M square feet of retail space. In partnership with JMA (for CBRS radios), Federated Wireless (for SAS), Druid (for Core EPC), Geoverse (for roaming), Cradlepoint (for modems and mobile routers), and Advanced Network Services (as the lead system integrator) deployed a private LTE network to handle traffic/parking management, digital signage, and other operational communications.

- Dallas Love Field airport: Boingo was one of the first neutral host operators to trial CBRS network deployment. In partnership with Commscope/Rucks (for CBRS access points) and Federated Wireless (for SAS), the company deployed a trial network at the Dallas Love Field airport to handle operational communications. Since its trial, Boingo has announced its plan to deploy the CBRS network at other venues where it has Wi-Fi and DAS networks.

A common theme that comes across all these private LTE network deployments based on CBRS is that enterprises see an opportunity to stand up reliable and secure private wireless networks that can handle mission-critical applications without relying on wired connections to establish secure channels and handle mobility.

A big challenge for Private LTE has been the spectrum. While giant mining company like Rio Tinto has the wherewithal to negotiate a deal with a local operator (e.g., Telstra in Australia) for sub-leasing spectrum, most manufacturing plants, retail malls, and other smaller enterprises would be less inclined to approach a major carrier for a sublease arrangement for licensed spectrum. Moreover, in the U.S., the mobile operators are less inclined to lease spectrum for non-mobile broadband applications as they are busy deploying their spectrum to meet the growing needs in their networks. With CBRS, this dynamic can change as the cheaper "licensed" spectrum under PAL, or even "unlicensed" under GAA, can be used for private LTE use knowing that SAS can help coordinate access and possible contention under the GAA operation.

Factors Influencing CBRS Market Development

The U.S. wireless industry is going through significant changes at the moment, as industry structure, and regulatory changes are impacting investment decisions of several large players. The introduction of CBRS is a minor issue in context of several key issues impacting the industry today. Some of those factors may significantly change the pace of CBRS market development and infrastructure investments, which can significantly impact our forecasts in this report. Some of these external factors are:

1. Timing of C-band auction -- Major operators are eager to get their hands on the C-band (3.7 – 4.2 GHz) spectrum. This mid-band is a crucial resource for the major operators, especially Verizon and AT&T, to significantly improve the breadth and depth of their 5G networks. T-Mobile is largely banking on its planned merger with Sprint for its "mid-band" spectrum for 5G. With the FCC's recent decision to take a public path for the C-band auction possibly late 2020 or early 2021, the immediate need for CBRS becomes a little bit more clear for Verizon, and possibly AT&T.

2. T-Mobile/Sprint merger, or dissolution of the planned merger -- While Mobile Experts believes that the T-Mobile/Sprint merger will happen in the first half of 2020, there is a possibility that the merger may not happen. If so, we believe T-Mobile may look to CBRS, in addition to the C-band, for its "mid-band" spectrum strategy. In such a case, the case for CBRS for mobility increases, and our CBRS forecast will rise.

3. Cable operators' facilities-based mobile strategy -- The pace of the cable operators' deployment of CBRS small cells on their cable strand networks will likely depend on the maturity of their EPC development and whether they can negotiate MVNO terms with Verizon to be able to use own CBRS small cell networks effectively. If the cable operators are not able to negotiate suitable MVNO terms to direct mobile traffic onto

own CBRS network, they may not pursue this strategy. Alternatively, if the cable operators can secure an "infrastructure-sharing" MVNO agreement (similar to the Altice/Sprint MVNO) whereby Verizon and Charter/Comcast can cooperatively share RAN capacity off of CBRS network deployed by the cable operators, then the pace of CBRS outdoor network deployment may pick up.

4. Mobile operator support of CBRS indoor cellular -- A CBRS network can function independently of each operator's spectrum, and offer shared access for everyone. Of course, major operators have to be onboard in allowing a neutral host operator to connect CBRS small cell networks to the operators' core networks for seamless roaming and access to operator services. Some operators do not like this approach because of the loss of control over the user experience. In particular, operators that take pride in the quality of their networks do not want to relinquish control to a neutral host provider such as Boingo, Crown Castle, etc. So, there are challenges of gaining acceptance and cooperation from the mobile operators, but CBRS private network solution has the elegance of low-cost shared infrastructure that can be used for private LTE applications and seamless coverage solutions for millions of smaller buildings across the U.S. that do not have adequate mobile coverage.

5. Enterprise LTE ecosystem maturity – Wi-Fi is synonymous with enterprise wireless networking, and it will continue to serve as a de facto enterprise wireless connectivity solution for a majority of non-critical, nomadic applications like laptop connectivity for checking emails and browsing. For mission-critical applications that require reliable, secure, and mobile connectivity solutions, private LTE systems offer compelling solutions especially with low-cost spectrum options like CBRS. For this "enterprise LTE/5G" market to flourish, the entire ecosystem of chipsets, devices, infrastructure, software, and system integrator must mature. We are seeing early signs of this ecosystem maturing with some Core EPC solutions offered through public cloud services, for example (e.g., Athonet on AWS, Ruckus on Azure, etc.) to make it more cost-effective to use. Also, venture capital is coming into this space with Celona securing $10M series A to launch private mobile networks for enterprises.

Expanding CBRS Ecosystem

The CBRS ecosystem has been steadily expanding since the CBRS Alliance, an industry body representing the interests of the CBRS ecosystem, was founded in 2016. Over the past three-plus years since the founding, the organization has grown to 150 members comprised of companies that have historically supported service provider community as well as enterprises. A diverse group of companies represented in the Alliance is a testament to potential impact that CBRS can make in both the operator- and enterprise-driven network deployments.

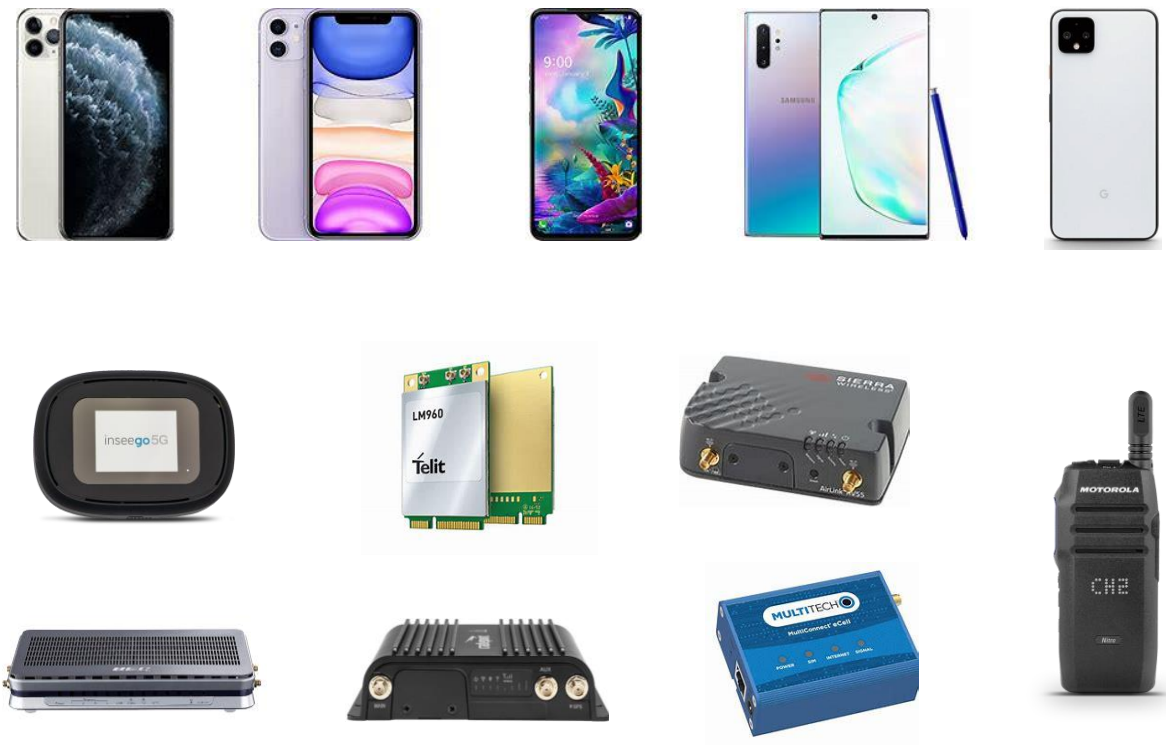
Of course, the sheer number of companies in an industry body does not truly reflect the health of the ecosystem. What good is an industry body or technical standards if no product is available to realize the potential of spectrum or standards? Fortunately, we are seeing a broad array of infrastructure and end user device products coming to market. According to the CBRS Alliance website, over 20 CBSD infrastructure products from 11 vendors are currently authorized to operate in the band.[6] As predicted, many more vendors had introduced CBRS small cells since last year when we had reported only 4 vendors with authorized CBRS small cell products.

Source: Ericsson, Nokia, Ruckus, Sercomm

Figure 5. Examples of Outdoor and Indoor CBRS small cells certified by the FCC

With two distinct CBSD categories, CBRS base stations coming to the market will include both Outdoor and Indoor small cells. Small cells typically use a highly integrated RAN structure with baseband and radio functionalities collapsed in an integrated design. One variation on this theme is small cell units that are broken into two physical boxes (such as Corning's Spidercloud small cells, Ericsson's Radio Dot, JMA's XRAN and CellHub), where some Layer 1/Layer 2 baseband processing is executed in the radio unit, and the rest of Layer 2/Layer 3 processing is done in a controller box for multiple radio units.

[6] It should be noted that the CBRS Alliance does not list all FCC-authorized devices, so there are more CBRS-certified devices in the marketplace.



Source: Company images

Figure 6. Examples of Authorized CBRS End User Devices

Similarly, we have seen a big jump in end user devices that support the CBRS band 48. While the topic of whether or not major tier-one smartphones would support CBRS band 48 was hotly speculated during the past year, this is no longer an issue. While we had predicted that most top-tier smartphones would have the CBRS band support by second half of 2019, we weren't sure about Apple. With iPhone 11 launch, that question has been answered. All three classes of iPhone 11 (11/Pro/Max) support the CBRS band 48! With dual-SIM features on most upper-tier smartphones, the stage is set for enterprises to take advantage of local CBRS network for offload or private LTE applications and using mobile operator networks for general public use. Besides Apple, the CBRS band is supported on latest tier-one smartphones from Samsung (Galaxy Note 10, S10, 5G), LG (G8 ThinQ, V50 ThinQ 5G), Google (Pixel 4), and OnePlus (7/Pro). In addition to smartphones, there are CBRS modules, gateways, routers, and other IoT devices, and two-way radios from Motorola. According to the CBRS Alliance, there are over 50 end user devices that support the CBRS band 48.

3 REGULATORY UPDATE

The final CBRS rules were approved and released on October 24, 2018. The updated rules settled the debate concerning the PAL license coverage area and licensing term duration, along with a few technical factors on the commercial use of the 3.5 GHz CBRS band. In essence, the updated CBRS rules set larger license coverage areas (county-size instead of census tract) and longer license terms (10 years with renewal instead of 3 years) vs. the original 2015 order. The final rule changes generally favor larger players (i.e., mobile and cable operators) while giving coordinated "free" access through lowest-tier access. Moreover, the FCC has set the date for PAL spectrum auction (June 25, 2020) and has provided some basic guidelines on minimum pricing. The regulatory certainty around PAL license availability is expected to help drive investment decisions of the different market players including major mobile and cable operators, WISPs, enterprises, and neutral host providers.

Final FCC Rules

The final FCC rules[7] concerning the CBRS band use settles a few long debates about the licensing size of priority licenses to the CBRS spectrum. Like any compromise, no one group seems pleased with the outcome, but bigger players including major mobile and cable operators seem generally pleased with the outcome compared to the smaller WISPs and enterprises. The larger license area and longer-term duration mostly likely set higher spectrum costs for PAL licenses, thus limiting broad adoption across the different market segments.

PAL Geographic License Area

One of the key contentions among the different stakeholders, large and small, has been the PAL license coverage area. The original CBRS rule set the license area based on census tract providing much smaller coverage area, hence granular and lower-cost license areas. While smaller players welcomed the possibility of obtaining cheaper "licensed" spectrum in targeted interest areas, larger players, including mobile and cable operators viewed this as too onerous and cumbersome to maintain many licenses to "stitch together" a larger mobile coverage footprint. Moreover, they argued that the small size of census tracts in denser areas creates overlapping border edges that increase the possibility of interferences with neighboring PAL licensees.

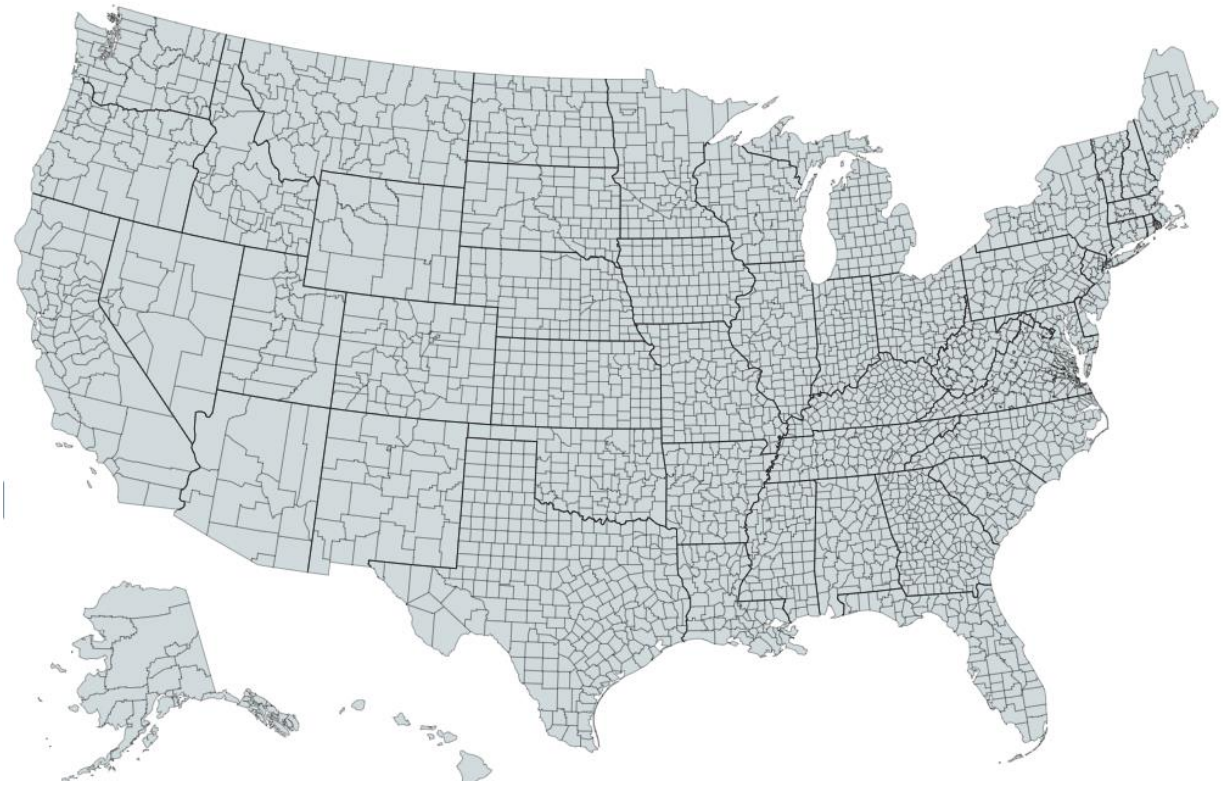
With over 74,000 census tracts in the USA, including Puerto Rico, geographic areas can vary widely depending on population density. For example, below is a map of more than 1,200 census tracts in Colorado. Notice the small census tract areas in the dense urban areas of Denver where a single census tract can encompass a few cities blocks while a census tract in

[7] https://docs.fcc.gov/public/attachments/FCC-18-149A1.pdf

rural areas of the State can encompass a county-wide area. Geographic size and the number of census tracts can vary widely. For instance, there are over 8,000 census tracts in California. In contrast, Wyoming has only 132 census tract areas in the state.

It is no surprise that major mobile operators who have dealt with much larger license areas would lobby for 416 Partial Economic Areas (PEAs) for PAL license size instead of 74,000 census tracts.

In the end, the FCC settled on the county basis for the PAL license area. Reducing the number of PAL licenses from 74,000 census tracts to about 3,000 counties is more palatable compromise for the major operators as well (and FCC auction administrators).



Source: worldatlas.com

Figure 7. New PAL license designation based on more than 3000 counties

PAL Licensing Term Duration

The original CBRS rules called for a three-year term with a one-time renewal extension. For major operators who make capital investment decisions with much longer-term horizons viewed the short license term with no renewal expectation as a non-starter. Congruent with its decision to expand the license area to larger county basis, the FCC ruled in favor of a 10-year renewal term for PAL licensing. The FCC went back to the time-tested licensing terms

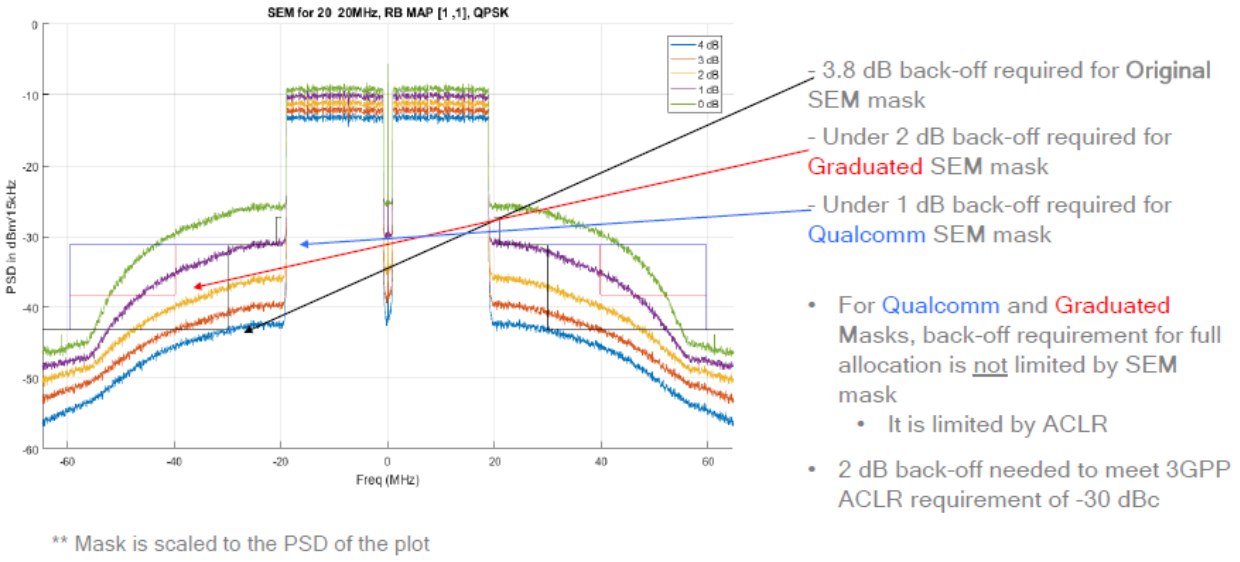
as a proven framework for major investments in this crucial mid-band spectrum for 5G services.

To ensure productive utilization of the spectrum instead of the spectrum "hoarding," the FCC has imposed performance requirements for PAL licensees. At the end of license term, each PAL license must show that it is providing "substantial" service in a license area. For mobile services, the "substantial" service requirement is 50% population coverage. For point-to-point fixed wireless, that requirement is either operate four or more point-to-point links for license areas with 134,000 population or less or a minimum number of links equal to the population in a given license area divided by 33,500. This performance requirement, either directly or under lease arrangement and opportunistic GAA use of the band, may provide opportunities for smaller players to address various market opportunities without heavy PAL spectrum investment. Moreover, the FCC approval of partitioning and disaggregation of PAL licenses on the secondary market may foster market-based approach for smaller "niche" market opportunities that larger players may not want to pursue.

Emission Limits

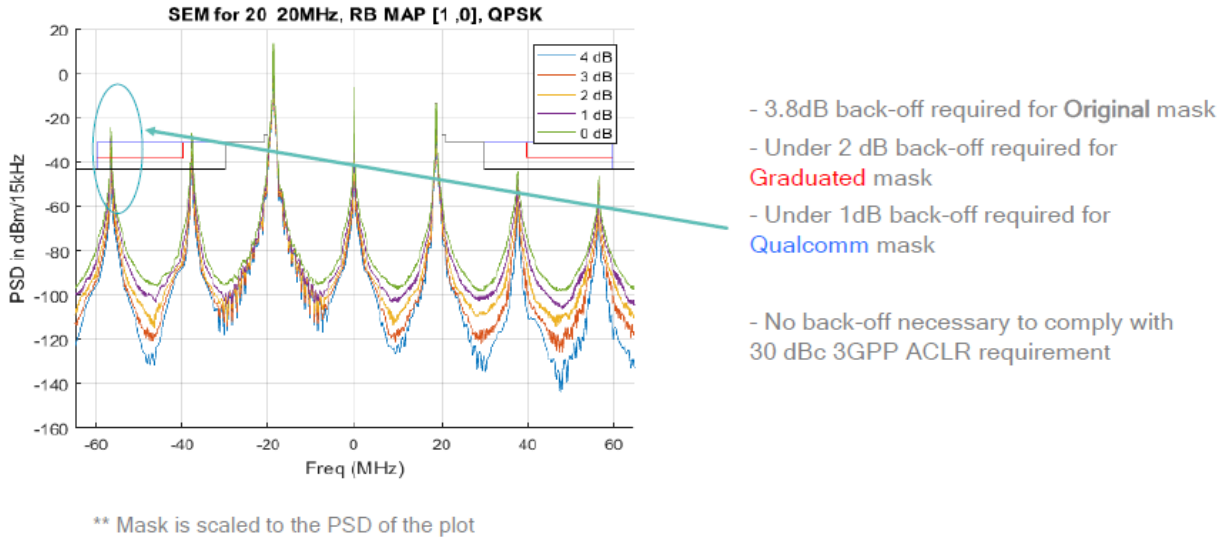
One of the key updates to the revised CBRS rules is the accommodation for some relaxation in the emission mask for uplink transmissions from end-user devices, i.e., smartphones to handle wider channel bandwidth beyond 10 MHz. Under the previous rule, a UE device operating with wider than 10MHz channel would require power reduction to protect an operation in adjacent bands. According to Qualcomm simulation results[8] (see figures below), revised out-of-band emission limits for UE devices and adjacent channel leakage requirement (ACLR) of -30 dBc, a 3GPP standard, would essentially allow wider than 10MHz channel operation with minimal power reduction.

[8] Qualcomm ex parte on "Additional technical information regarding CBRS emission proposals," March 14, 2018



Source: Qualcomm

Figure 8. Full resource allocation in a 40MHz channel limited by 3GPP ACLR requirement



Source: Qualcomm

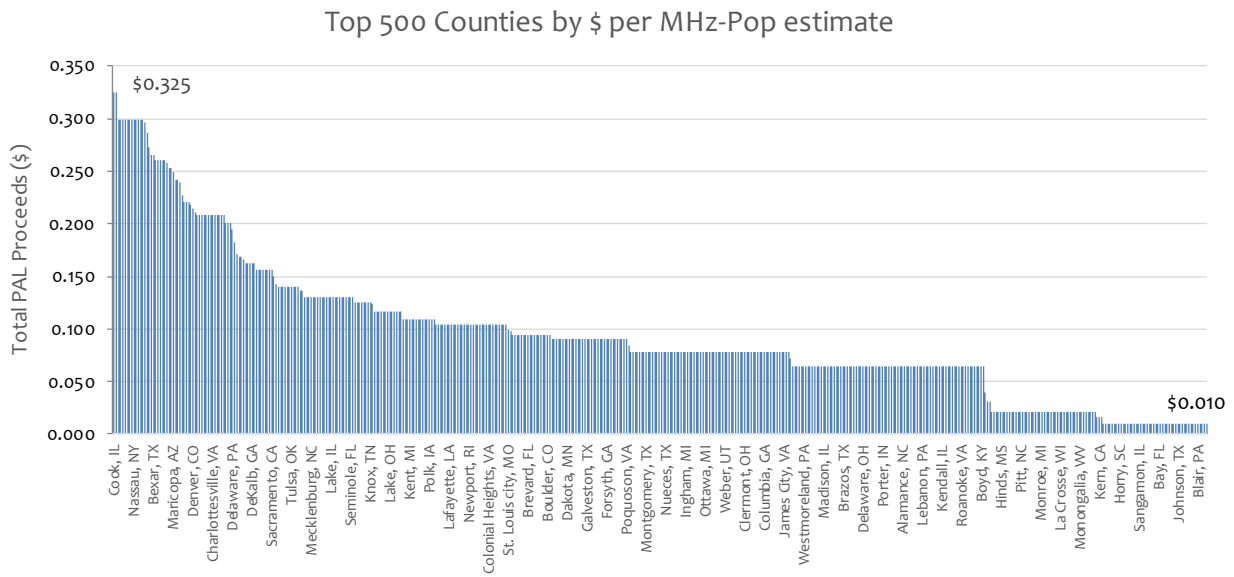
Figure 9. Low resource allocation in a 40MHz channel limited by proposed emission mask

In other words, CBRS-enabled smartphones sold in the USA don't have to be "non-standard" devices and keeps timing and availability of CBRS-enabled smartphones in concert with mid-band 3.5GHz devices coming to market elsewhere. This "relaxation" on emission mask of uplinks from end devices like smartphones helped facilitate a broad array of CBRS-enabled smartphones to come to market this year, as noted earlier.

PAL Spectrum Valuation

The FCC has proposed some guidance on the upcoming CBRS PAL spectrum auction (Auction 105) scheduled to commence on June 25, 2020.[9] In last year's report, we had guided that a CBRS PAL license (for a 10MHz channel) would cost somewhere between $0.02 to $0.70 per MHz-Pop depending on county population density and other factors. It is reassuring to note that the FCC's public notice on PAL auction, released on September 27, 2019, has set a minimum opening bid of $0.02 per MHz-Pop with a minimum of $1000. So, our rough estimate laid out in last year's report appears in the "ballpark."

Since our 2018 CBRS report, Mobile Experts published a separate report on "CBRS PAL Spectrum Valuation" (published in May 2019).[10] Based on that report, we have estimated that a PAL license would cost about $0.325 per MHz-Pop in dense counties encompassing major cities like Cook County, Los Angeles County, etc., and about $0.003 per MHz-Pop in very rural counties.



Source: Mobile Experts

Figure 10. CBRS PAL Spectrum Cost Estimates for Top 500 Counties

In terms of absolute dollar figures, our analysis indicates that Los Angeles is the most expensive market with seven PAL licenses costing well over $200M. NY County, in comparison could cost about $20M for the same amount of spectrum. The big difference between the two markets is that Los Angeles County has a much larger geographic area covering a lot more population versus significantly smaller geographic footprint of the NY

[9] https://www.fcc.gov/auction/105

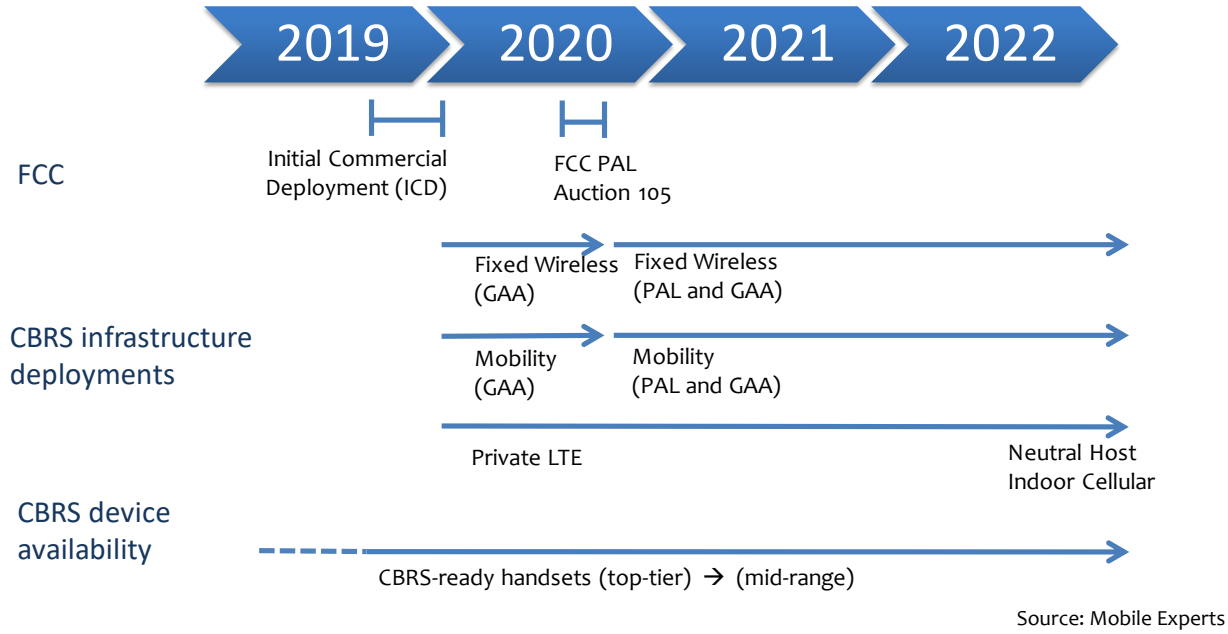
[10] Expert INSIGHT report: "CBRS PAL Valuation," May 2019.

County covering about 1/6th of the population. For a rural county like Bonner, Idaho, a 10MHz PAL license could cost less than the $1000 minimum bid.

Based on our analysis of the supply (i.e., seven 10MHz PAL licenses per county) and demand (i.e., potential bidders ranging from mobile and cable operators, WISPs and enterprises), the PAL spectrum auction could raise about $2.2B, with an average PAL license costing around $100,000. The top 200 out of over 3000 counties in the USA, holds about 90% of the total PAL spectrum valuation. In the top 400 or so counties where the majority of the population resides, a PAL spectrum cost is estimated at least $0.06 per MHz-Pop.

Commercialization Timeline

Five of six conditionally approved SAS providers have been approved by the FCC, including Federated Wireless, Google, Commscope, Amdocs, and Sony. Since the Initial Commercial Deployment (ICD) launch in September 2019, several of the SAS vendors have submitted their ICD test results of real-world field operation of end-to-end systems, including SAS, CBSDs, and end user devices. The FCC, NTIA, and DoD are expected to complete their reviews and provide the final "green light" for full commercial deployments by the first quarter 2020.



Source: Mobile Experts

Figure 11. CBRS Commercialization Timeline

Mobile Experts expect major SAS providers to complete their ESC sensor network rollout by the end of 2019 although there is a chance that a buildout in parts of the U.S. coasts far away from major naval bases to be completed in early 2020. The initial CBRS infrastructure

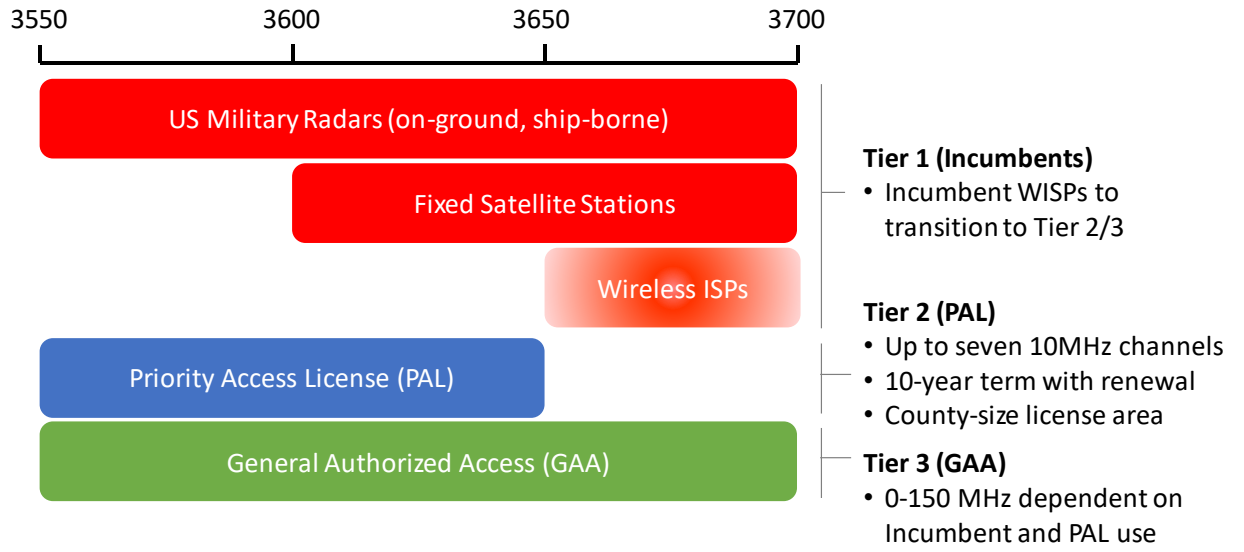
deployments will largely be inland for fixed wireless and some Private LTE applications. Once the PAL auction is completed (sometime in the third or possibly the fourth quarter of 2020), we expect CBRS infrastructure rollout to ramp up more quickly, especially by the major operators for the mobile broadband application. In terms of end devices, the penetration of CBRS-ready handsets will reach a meaningful share (30-40%) of the installed base during 2022 - 2023. Once that inflection point is reached, we expect to see a more robust activity around neutral host deployments for indoor cellular use to pick up the pace from the initial private LTE applications driving enterprise adoption in key vertical industries including mining, utility, transportation, industrial warehousing, and manufacturing.

4 TECHNOLOGY BACKGROUND

Various technology "pieces" for CBRS came together during 2019. The FCC certified several Spectrum Access System (SAS) for the Initial Commercial Deployment launch in September, and leading Environmental Sensing Capability (ESC) radar sensing networks are expected to come online by the end of the year. The Wireless Innovation Forum and the CBRS Alliance have diligently published technical baseline standards and worked with various government agencies and leading industry players to bring numerous certified products to the market. As we near full commercialization of the CBRS band, major industry baseline standards for interoperability between SAS, ESC, infrastructure, and end user devices are now in place. The industry bodies will continue their work towards coexistence refinement and CBRS for 5G as the CBRS ecosystem expands across both carrier- and enterprise-driven use cases.

CBRS Overview

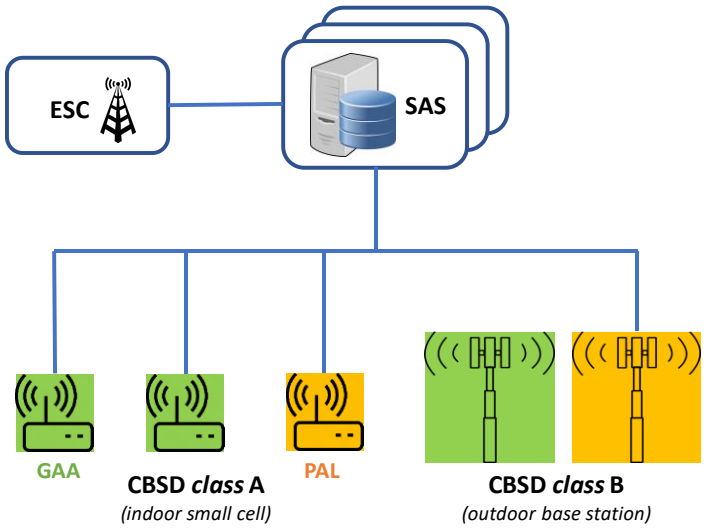
In 2015, the U.S. Federal Communications Commission (FCC) formally established *Citizen Broadband Radio Service* (CBRS) for shared commercial use of the 3.5 GHz band (3550-3700 MHz) with incumbent military radars and fixed satellite stations. For the first time, dynamic spectrum sharing rules have been defined to make additional spectrum available for flexible wireless broadband use while ensuring interference protection and uninterrupted use by the incumbent users. Under the plan, a three-tier sharing paradigm coordinates spectrum access among the incumbent military radars and satellite ground stations and new commercial users. The three tiers are *Incumbent*, *Priority Access License* (PAL), and *General Authorized Access* (GAA) users.



Source: Mobile Experts

Figure 12. CBRS Spectrum Authorization (Three-Tiered) Framework

A key element of the CBRS spectrum sharing architecture is the *Spectrum Access System* (SAS). A SAS maintains a database of all CBRS base stations, formally referred to as *Citizens Broadband Radio Service Devices* (CBSDs), including their tier status, geographical location, and other pertinent information to coordinate channel assignments and manage potential interferences. To mitigate possible interference to tier 1 military radar systems, the *Environmental Sensing Capability* (ESC) is deployed in strategic locations near naval stations, mostly along coastal regions, to detect incumbent activities. When incumbent use is detected, the ESC alerts the SAS, which then directs CBSDs utilizing impacted CBRS channels in that area to move over to other channels. The cloud-based SAS enforces the three-tier spectrum sharing mechanism based on FCC rules via centralized, dynamic coordination of spectrum channel assignments across all CBRS base stations in a region.



Source: Mobile Experts

Figure 13. CBRS Functional Overview

The CBRS rulemaking defines two classes of base stations: *Category A* and *Category B*. A Category A device can be thought of as indoor or low-power outdoor small cells with a maximum conducted the power of 24 dBm (per 10 MHz) and maximum EIRP of 30 dBm (1 watt). This type of small cell is similar to "enterprise" class small cells with ~250mW transmit power with a typical 2 dBi omni antenna or up to 6 dBi directional antenna. Meanwhile, a Category B device is meant for outdoor use with a maximum EIRP of 47 dBm (50 watts). With a very high-gain antenna, outdoor CBRS devices can be used for fixed wireless purposes, for example. While indoor and outdoor small cell or access point can operate as either GAA or PAL, we expect to see more GAA deployments inland until ESC certification and PAL auctions take place.

As of the ICD launch event in September, the FCC has certified five SAS systems: Federated Wireless, Google, Commscope, Sony, and Amdocs. The first three SAS vendors have been very active in the market, establishing partnerships and commercial agreements with operators, vendors, system integrators, venue owners, and enterprises. Major SAS vendors have submitted ICD reports and are now awaiting final approval from the government agencies for full commercialization. Federated Wireless has been aggressive in its ICD plan touting over thousands of sites. Meanwhile, Google has been active in courting WISPs in the fixed wireless segment. Meanwhile, Commscope has been active in AT&T's fixed wireless deployment and other fixed wireless and some in-building wireless engagements. Commscope's Ruckus division is also very active in the enterprise private LTE engagements, where it is involved in several ICD trials, including Times Square deployment with Connectivity Wireless.

CBRS Radio Classification

In FCC parlance, a CBRS eNodeB radio is officially classified as *Citizen Broadband Radio Service Device* (CBSD). CBSD devices are categorized into two classes. Including end user devices, CBRS radios can be classified into three types:

- Category A CBSD
- Category B CBSD
- End User Device (EUD)

CBSD Category A devices are generally viewed as "CBRS indoor small cells" as they are permitted maximum EIRP of 30 dBm or 1 watt of transmit power (per 10 MHz channel) or power spectral density (PSD) of 20 dBm per MHz.[11] Category A CBSD devices are required to operate indoors with antenna height less than 6 meters above average terrain. It should be noted that when a Category A CBSD device registers with a SAS, it must communicate the following attributes so that SAS can manage the shared spectrum usage:

- Geographic location;
- PAL or GAA authorization status;
- FCC identification number, call sign, user contact information;
- Air interface technology (e.g., LTE, proprietary);
- Unique manufacturer's serial number;
- Indoor or Outdoor operation; and,
- Sensing capabilities (if supported).

Although we typically think of Category A CBSD devices as being CBRS indoor small cells, they can be deployed outdoors with ruggedized housing to protect them from the

[11] Power spectral density (PSD) measures the power present in the signal as a function of frequency. It is effectively EIRP divided by the amount of spectrum committed.

environment. Some of these "low power" outdoor units may be found in enterprise deployments where long-range may not be necessary in certain use cases.

CBSD Category B devices are considered "CBRS outdoor small cells" as they have a higher permitted maximum EIRP of 47 dBm or 50 watts of transmit power (per 10 MHz channel) and must operate outdoors by rule. Category B CBSD devices must operate outdoors and must be professionally installed by certified installers. Also, the antenna heights are expected to be higher than 6 meters above average terrain. When a Category B CBSD device registers with a SAS, it must communicate the Category A attributes already highlighted above, plus the following additional information:

- Antenna gain, beamwidth, azimuth, and down-tilt angle; and,
- Antenna height above ground level;

Although we typically think of the Category B CBSD devices as being infrastructure units, in some fixed wireless deployments, the subscriber CPE units can be categorized as CBSD Category B devices based on RF characteristics and the fact that some of these outdoor CPE units are installed high above the ground level. For example, in AT&T fixed wireless deployment, it is using Category B devices as subscriber CPE units to maximize the coverage reach of its CBRS fixed wireless network.

End User Device (EUD) category represents end terminal devices such as smartphones, modules, IoT router/gateway type of products. The CBRS EUD devices are permitted maximum EIRP of 23 dBm or 200 mW (per 10 MHz channel). It is expected that these devices operate only if they can successfully receive and decode authorization signal transmitted by CBSD small cells.

In summary, the CBRS radio equipment can be classified into three CBSD types primarily based on RF performance and antenna height requirements, as shown below.

CBSD Device class	Maximum EIRP (dBm / 10 MHz)	Power Spectral Density (dBm / MHz)	Antenna Height (meters)
CBSD Category A	30 dBm (1 watt)	20 dBm	less than 6 meters
CBSD Category B	47 dBm (50 watts)	37 dBm	greater than 6 meters
End User Device (EUD)	23 dBm (200 mW)	n/a	n/a

Source: Mobile Experts

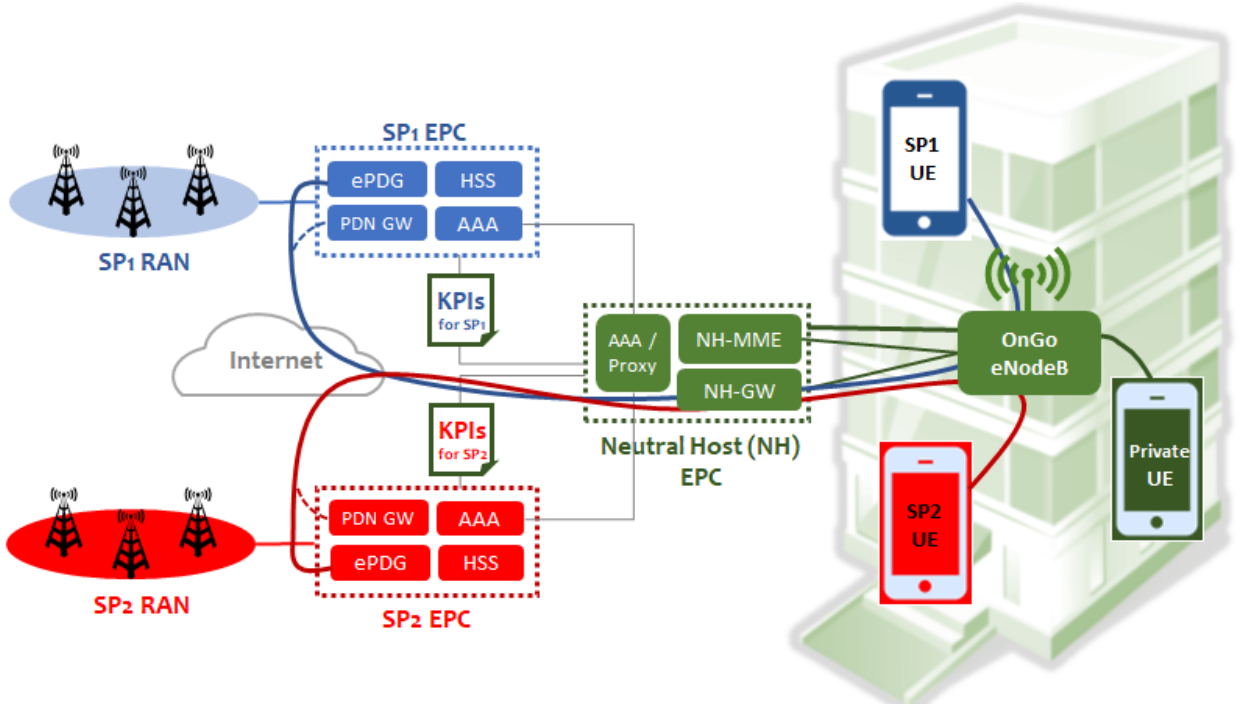
Figure 14. CBRS Device Types

Core Network Connectivity

Operators don't want to deal with setting up EPC connections to every new building and every neutral host that enters this market. At the same time, enterprises and some neutral hosts don't have the right contacts to coordinate with all of the operators' core networks. So, there is a new opportunity here for a Neutral Host Network operator to take a "clearinghouse" role in authenticating and setting policy for the operators and possibly running in-building wireless networks on behalf of enterprises.

Here, connection to the Core Networks is key because each handset that enters the building must be authenticated to access mobile network services. In addition to authentication and authorization, other policy and control functions specified by the operators must be enforced in order to ensure consistent user experience. Individual connections to each service provider's EPC would be duplicative and inefficient. We expect this market to quickly move to a few key aggregators, possibly led by some of the leading SAS providers or neutral host wireless infrastructure providers like the tower companies.

Managed services through a neutral host network (NHN) provider requires integration of core networks between the NHN and multiple network operators, as shown below. The interworking between NHN and multiple operators can leverage the WLAN internetworking architecture as defined in 3GPP. A mobile device can use ePDG to gain access to an operator's IP services, including voice services over IMS. The service continuity is maintained between NHN and an operator network, and local IP services (e.g., enterprise PBX) can be provided through local breakout at the neutral host network. Another key aspect of the NHN core network is to provide key performing indicators (KPIs) or charging metrics to operator's core network through NHN EPC. Since the NHN, in this case, needs to meet the CBRS governing rules, the NHN core also needs to interface with SAS for dynamic channel assignments through the CBRS Gateway as necessary.



Source: Mobile Experts

Figure 15. Core network connectivity between a Neutral Host and Mobile operators

Roaming onto Neutral Host Network (NHN) leverages the same cellular roaming principles and procedures as roaming onto another operator's network. A UE device first discovers a CBRS network by scanning the CBRS frequency band for a network broadcasting the CBRS Shared Home Network Identifier (HNI)[12]. The device then determines if the network supports Neutral Hosting and reads the list of Participating Service Provider IDs (PSP-IDs). It should be noted that if a service provider has a commercial roaming agreement with the NHN operator, then the neutral host network would be broadcasting the participating service provider's network identifier PLMN-ID[13] in its list of PSP-IDs. If the device is pre-provisioned to access any of the listed PSP-IDs, it would then begin to attach and authenticate to the NHN network to roam. As a part of the neutral host commercial arrangement, the service provider is responsible for pre-provisioning one or more corresponding CBRS identifiers, CBRS-I onto device SIM, so that its "NHN-capable" devices can discover and attach to allowed neutral host networks. The CBRS Alliance, in close collaboration with ATIS, which manages IMSI[14] resources in the United States, assigns IMSI identifiers for the CBRS use case.

[12] A Shared HNI is shared among multiple operators in the CBRS spectrum. NHN operators can use a PLMN-ID assigned for shared CBRS use or apply for own PLMN-ID as CBRS-I.

[13] PLMN-ID (Public Land Mobile Network Identifier) is a unique identification of a service provider, comprised of MCC (mobile country code) + MNC (mobile network code).

[14] IMSI (International Mobile Subscriber ID) is a 15-digit unique identifier for each mobile user device. For CBRS/OnGo use case, the 9-digit mobile subscriber ID is further partitioned into 4-digit IMSI Block Number(IBN) and 5-digit User Identification Number (UIN) resulting in 10,000 blocks of 100,000 IMSI's.

Once a UE device has selected or roamed onto an NHN, the data connection between NHN and the mobile operator can operate in either "trusted" or "untrusted" mode. In "trusted" mode, an NH-GW connection to the participating mobile operator's PDN-GW uses the standard 3GPP interface. In "untrusted" mode, an NH-GW connection between user device and mobile operator network services is handled through secure IPsec tunnel via the Internet to mobile operator's ePDG, which manages the interworking between the operator's EPC and untrusted non-3GPP networks such as Wi-Fi or neutral host CBRS network.

CBRS Standards

The Wireless Innovation Forum (WinnForum) is a non-profit standard development organization that has played a key role in establishing technical standards based on FCC rules. Through its Spectrum Sharing Committee (SSC), the WinnForum established a baseline of CBRS standards, which can be found on the WinnForum site (https://cbrs.wirelessinnovation.org/release-1-standards-specifications).

Identifier	Specification	Date
WINNF-TS-0016	SAS to CBSD Technical Specification (v 1.2.4)	June 27. 2019
WINNF-TS-0022	CBRS PKI Certificate Policy (v 1.3.1)	May 21, 2019
WINNF-TS-0061	WG4 SAS Test and Certification Specification (v 1.5.1)	Oct. 7, 2019
WINNF-TS-0065	CBRS Communications Security Technical Spec. (v 1.1.1)	Feb. 6, 2019
WINNF-TS-0071	CBRS operational Security Technical Specification (v 1.0.0)	July 26, 2017
WINNF-TS-0096	SAS-SAS Protocol Technical Specification	Feb. 8, 2019
WINNF-TS-0112	CBRS Operational and Functional Requirements (v 1.8.0)	June 26, 2019
WINNF-TS-0122	CBRS CBSD Test Specification (v 1.0.1)	Dec. 19, 2017
WINNF-TS-0245	Operations for CBRS: PAL Database Technical Spec. (v 1.0.0)	July 26, 2017
WINNF-TS-0247	CPI Accreditation Standard (v 1.2.1)	July 12, 2019

Source: Mobile Experts

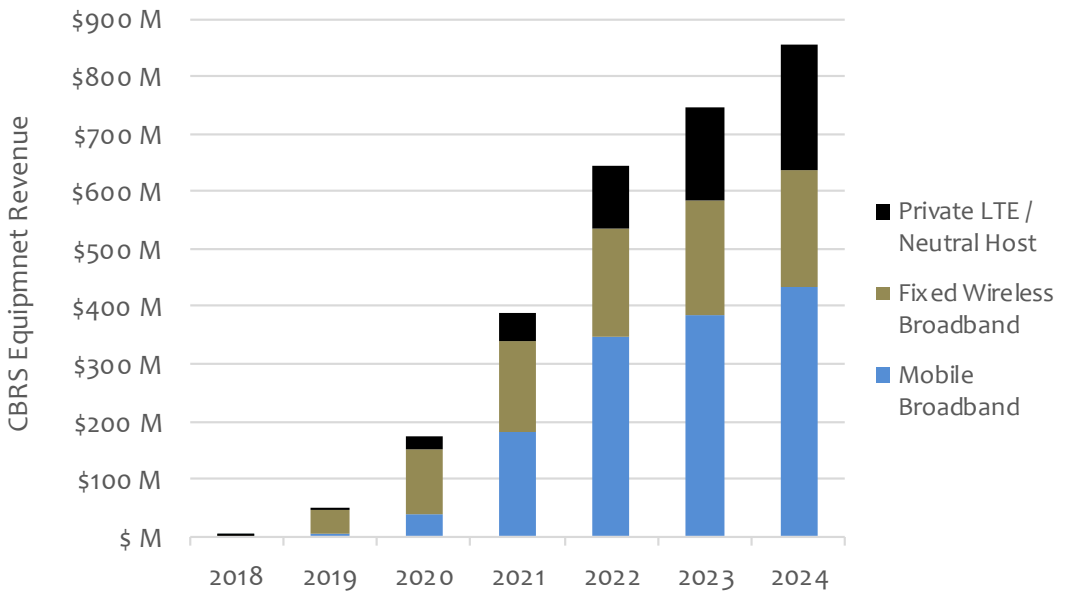
Figure 16. CBRS Standards

5 CBRS EQUIPMENT MARKET OUTLOOK

A commercial ramp of the CBRS market has been a long journey for market participants. In last year's report, we had expected the CBRS commercial launch to have started during the third quarter of this year – which didn't happen. Instead, the Initial Commercial Deployments (ICD) officially kicked off in September 2019, reaching a major milestone for the industry. Since the ICD launch in September, several CBRS trials and commercial launch plans have been announced. For example, AT&T announced its commercial plan on the CBRS spectrum to extend its fixed wireless broadband footprint across 18 states. Several private LTE network trials were also announced, including American Dream entertainment complex in New Jersey, Angels Stadium in California, and Times Square in NYC as some notable examples. Besides these private networks, we are aware of Verizon's use of CBRS band to increase its public cellular network capacity. Also, cable operators have been conducting both fixed wireless and mobile trials in several markets. While the full commercial launch hasn't officially begun, we believe the underlying demand from a range of stakeholders including large mobile and cable operators to enterprise and neutral host operators has not diminished.

CBRS Equipment Market by Application

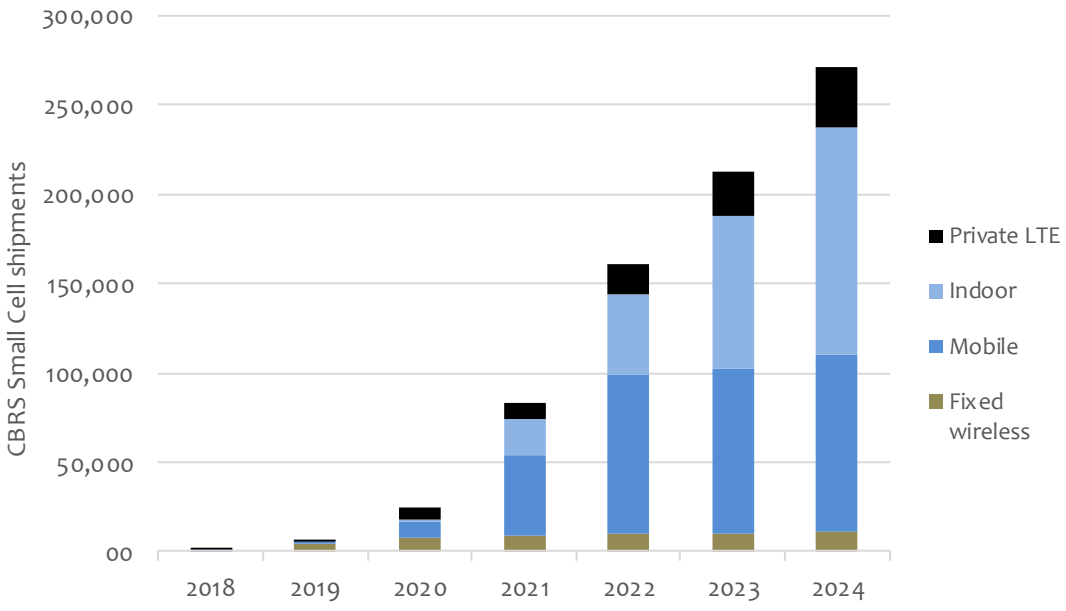
Mobile Experts expects that a full commercial launch will earnestly begin in 2020 once the FCC, NTIA, and DoD to give their final "green light." With the scheduled PAL auction taking place in June 2020, this milestone will provide certainty around major operator deployments of CBRS network infrastructure for mobility offload. While the initial commercial ramp will be led by fixed wireless deployments by telcos and wireless ISPs in rural and suburban markets, the future growth will come from mobility and private LTE use cases in urban and enterprise markets. The CBRS equipment market, including small cell infrastructure and end user devices ranging from CPEs, IoT gateways, mobile routers, and modules, is forecasted to grow quickly to over $850M by 2024. At the end of our forecast period, the mobility segment will constitute just over 50% of the CBRS equipment market, followed by private LTE (26%) and fixed wireless access (24%).



Source: Mobile Experts

Chart 2: CBRS Equipment Revenue by Application, 2018-2024

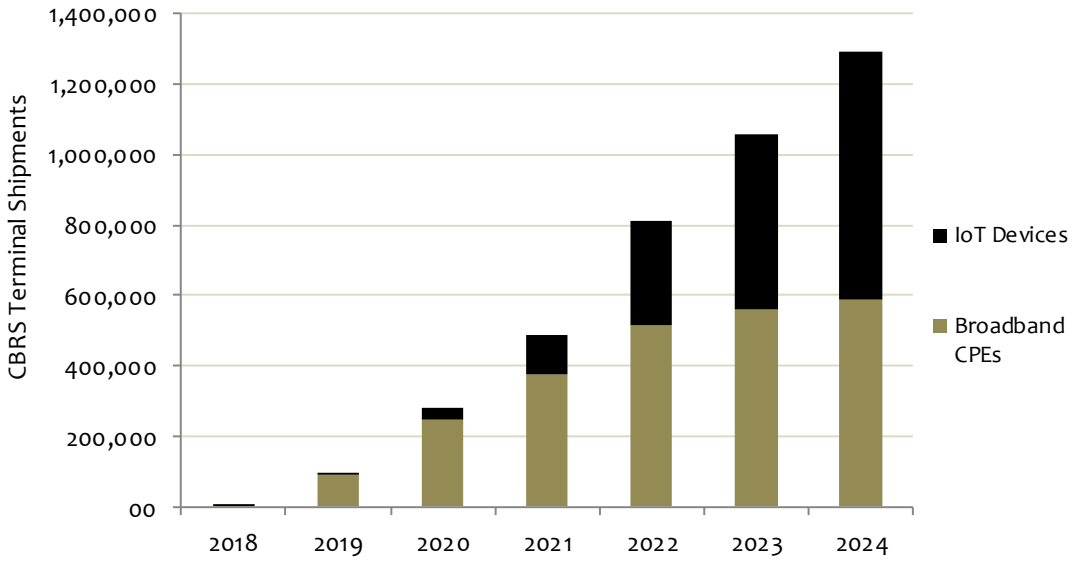
The annual CBRS equipment spending by the different use cases ranging from fixed wireless access, mobility offload (indoor and outdoor), and private LTE applications translate into the following CBRS infrastructure (Chart 3) and end user device (Chart 4) shipments.



Source: Mobile Experts

Chart 3: CBRS Infrastructure Shipment by Application, 2018-2024

The CBRS-enabled small cell infrastructure, also known as CBSDs, is forecasted to rise ten-fold from about 25,000 units in 2020 to over 270,000 units in 2024. The mobile offload and private LTE applications will drive the majority of those units with a major portion of those being lower-power indoor units.



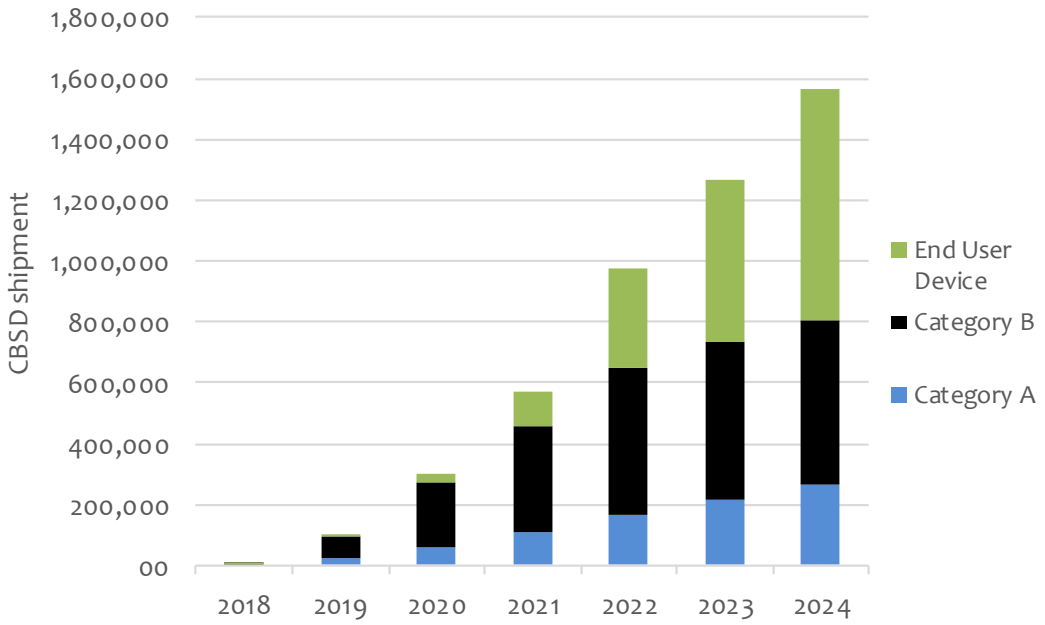
Source: Mobile Experts

Chart 4: CBRS End User Device Shipment by Application, 2018-2024

Excluding CBRS-enabled smartphones, the initial terminal deployment will be dominated by fixed wireless broadband CPEs as WISPs leverage the "incumbent" 3.65 – 3.7 GHz band (under Part 90 rules) for fixed wireless access until that band falls under the CBRS (Part 96) rules in April 2020. Over time, the IoT devices, such as fixed and mobile gateways/routers, USB dongles, two-way radios, etc., will become a more significant portion as private LTE and general mobile applications become more widely adopted in 2021 and beyond. Excluding smartphones, The CBRS-enabled CPE and IoT device shipment is forecasted to rise from less than 100k units in 2019 to about 1.3M units in 2024.

CBSD Category Shipment Forecast

In terms of the CBRS Device (CBSD) class categories – Class A (mid-power), Class B (high power), and End User Device (low-power EUD) – the overall CBRS infrastructure and device shipments will be dominated by Category B class CBSDs in the next few years as operators deploy these high-power infrastructure units for fixed wireless and mobile applications. For fixed wireless applications, major portion of broadband CPEs is likely to be Category B class CBSDs to maximize the coverage and capacity reach of fixed wireless links. As private LTE and indoor applications ramp up in the later years, the EUD class CBSDs will overtake the other two device categories.

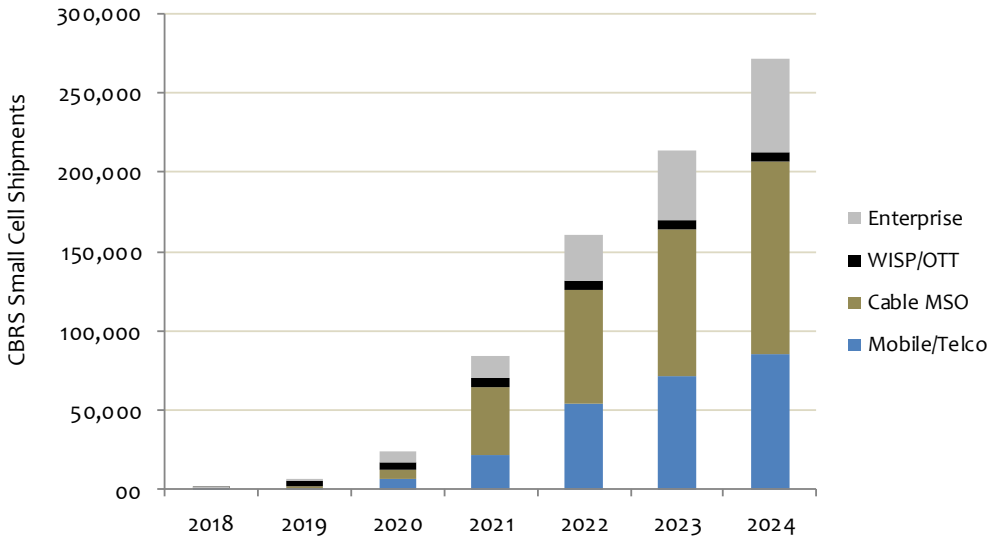


Source: Mobile Experts

Chart 5: Overall CBSD Category Shipments, 2018-2024

CBRS Deployment by Operator Type

The final CBRS spectrum rules reflect the compromises of both big and small players. Major mobile operators would have preferred traditional licensing terms based on large geographic coverage areas such as Partial Economic Areas (PEAs) but settled on county-size coverage areas. Meanwhile, smaller WISPs would have preferred the original three-year licensing duration to make the PAL spectrum licenses low-cost but settled on a ten-year term with renewals. In other words, CBRS offers something for everyone and tries to appeal to a wide range of players looking to deploy wireless infrastructure on this "innovation" band. Mobile Experts believe that the initial CBRS infrastructure deployments will be led by WISPs and enterprises and neutral host providers, but major mobile and cable operators will lead the majority of infrastructure deployments in later years for mobile offload and fixed wireless applications. The CBRS small cell unit shipment is forecasted to rise ten-fold from less than 25k units in 2020 to over 270k units in 2024. Compared to last year's report, our forecast has been reduced meaningfully for a couple of factors: a six-month delay in CBRS commercial launch (from second half 2019 to early 2020); and, a reduction in cable operator deployments.



Source: Mobile Experts

Chart 6: CBRS Small Cell Shipment by Operator Type, 2018-2024

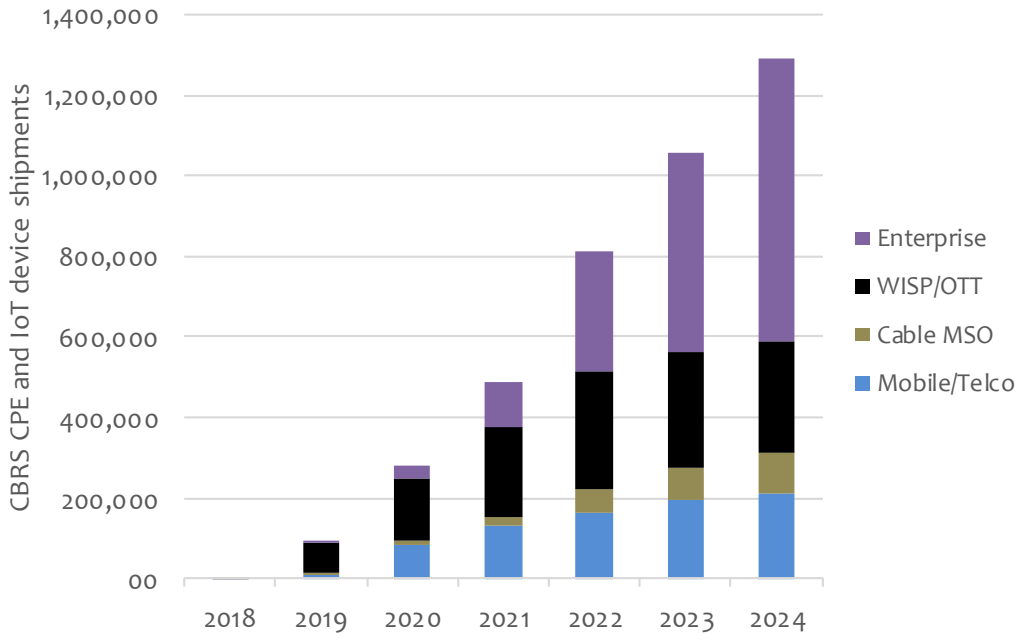
Mobile and telco operators will deploy a major portion of CBRS infrastructure for years to come. CBRS offers a new spectrum resource to increase mobile network capacity for some and another spectrum option to extend fixed wireless broadband footprint for others. For example, AT&T has already announced its plan to deploy CBRS small cells for fixed wireless applications across 11 states. Meanwhile, Verizon is in the process of bringing hundreds of CBRS multiband small cells online in anticipation of full commercial launch. Leveraging CBRS bands for carrier aggregation is an effective means to increase network capacity – akin to LAA but at a bigger scale[15], and we expect other operators to follow suit in later years.

Even though we have reduced the cable operator deployment of CBRS small cells in this year's forecast, they are still the dominant stakeholder in CBRS infrastructure deployments. The economic (and time-to-market) advantages of stand-mount small cells along with the possibility of spectrum ownership through CBRS make the cable operator deployment of CBRS infrastructure very appealing. After the PAL auction in 2020 and MVNO re-negotiation between cable operators and the host mobile operators, we expect to see a ramp-up of cable operator deployments of CBRS small cells – either as a part of "infrastructure sharing" MVNO model in coordination with the host mobile operators or as standalone mobile offload network.

[15] Using CBRS for mobile capacity augmentation is sometimes referred to as "LAA on steroid" since secondary carriers on the CBRS band can be transmitted at a higher power than LAA 5GHz. Thus CBRS "capacity" layer is much larger than LAA layer.

Wireless ISPs will drive the near-term CBRS small cell deployments or upgrade to the CBRS (Part 96) rules. By our estimate, over 10,000 fixed wireless access points are operating under the old Part 90 rules (in the 3.65 – 3.70 GHz band). A big portion of these Part 90 infrastructure devices has authorization grants to operate under Part 96. Although these units are already deployed, we have accounted for them under "shipment" in 2019 and 2020. Also, we are aware of thousands of units that can be upgraded via software to operate under Part 96. Mobile Experts forecast a steady shipment of CBRS small cells by the WISPs. The WISPs have other spectrum alternatives like 2.5 GHz and 5 GHz, so that the CBRS infrastructure will be another option in their "toolbox."

The enterprise use of CBRS small cells for private LTE applications will make up a meaningful share (over 20%) of CBRS infrastructure deployment during the forecast period. There are already thousands of enterprise deployment in the 3.65 GHz band, and we expect to see about 60k CBRS small cell shipments by 2024 for a wide range of industrial applications ranging from port operations, video surveillance cameras, warehouse automation, two-way radio communication, and many other operationally-oriented IoT applications. A growing number of CBRS infrastructure and IoT devices ranging from modules, mobile routers, fixed gateways, etc. are already available, and we are seeing IoT device vendors working on cost-optimized modules to expand the market further.



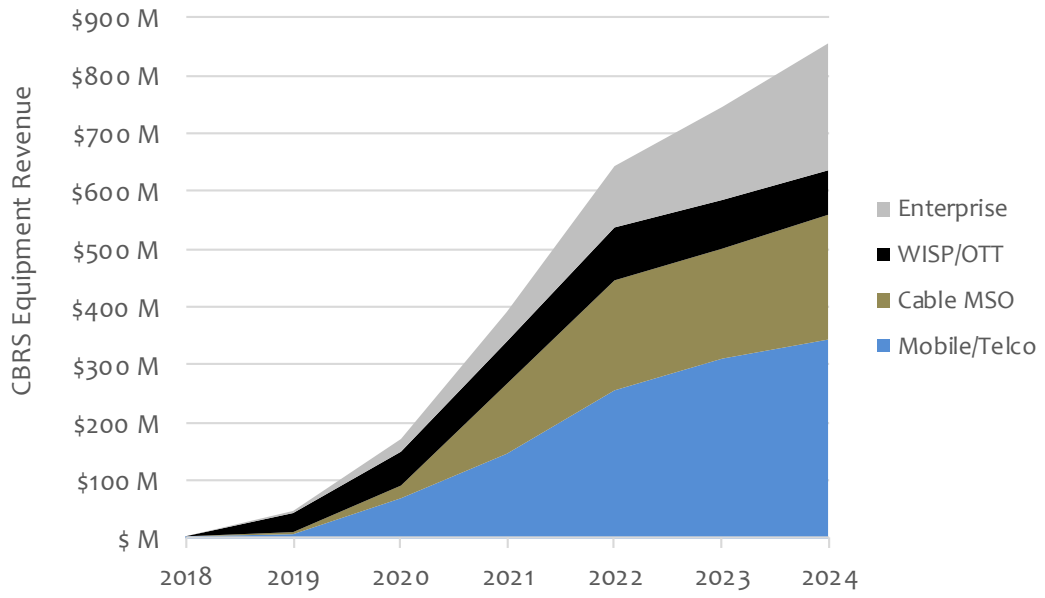
Source: Mobile Experts

Chart 7: CBRS End Device Shipment by Operator Type, 2018-2024

The growth in CBRS end device shipments is expected to rise slightly faster than the growth in CBRS small cell infrastructure. A big driver of that comes from an increasing shipment of

IoT devices, including fixed and mobile gateways/routers, modules, and other enterprise-centric devices, including tablets, laptops, and two-way radios. Outside of the enterprise IoT devices, the fixed wireless broadband CPEs will make up the majority of end device deployments by mobile and cable operators and WISPs. For cable operator deployment, about half of the 100k unit shipment in 2024 is fixed wireless CPEs while the other half are CBRS-enabled home gateways. There is a bit of uncertainty around cable operator CPE deployments at this point. If the cable operators decide to ramp up their wireless footprint through DOCSIS home gateways significantly, then the cable operator share of end device shipment can rise very dramatically. However, this is a low-probability scenario in our opinion, but our forecast does account for this.

It should be noted that about 80k CPE units attributed to the WISPs in 2019 are old Part 90 subscriber units that have been granted (CBRS) Part 96 authorization. The "real" shipment of CBRS subscriber CPE units will earnestly ramp up in 2020. The overall CBRS end device market, including broadband CPEs and IoT devices, is expected to reach about 1.3M units by 2024.



Source: Mobile Experts

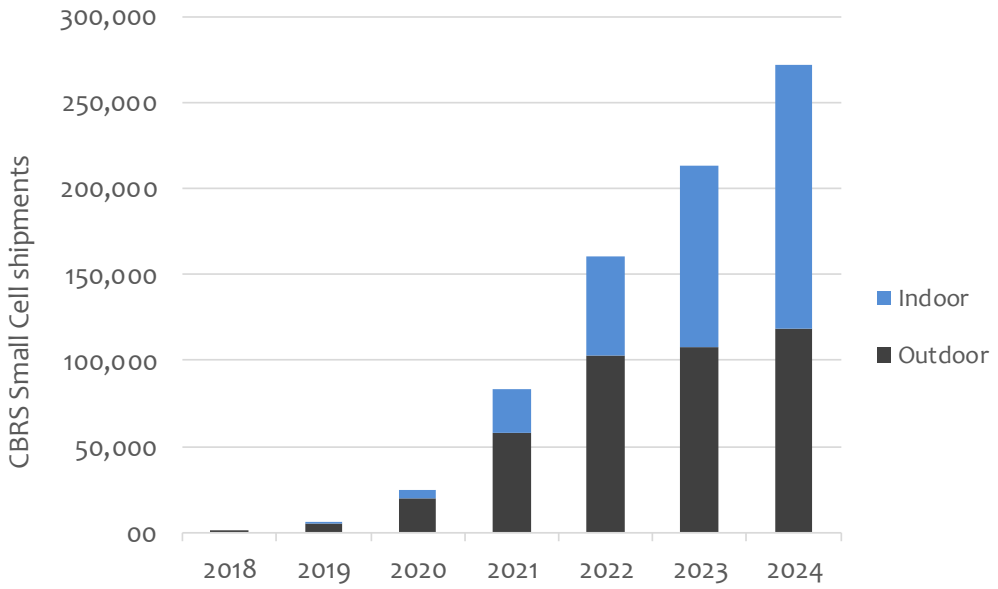
Chart 8: CBRS Equipment Spend by Operator Type, 2018-2024

Accounting for both CBRS infrastructure and end device spend, the mobile operators and WISPs will initially lead the CBRS equipment market as they look to expand mobile network capacity and expand fixed wireless broadband services. The mobile operator spending on CBRS equipment will grow steadily to about $350M in 2024, representing about 40% of the overall market. WISPs will be steady spenders of CBRS equipment at about $80-90M annually, representing about 9% of the overall market in 2024. Meanwhile, the cable

operator spending will ramp up slowly due to commercial issues around leveraging CBRS infrastructure for mobile use. Charter and Comcast need to work out commercial and operational terms with Verizon for MVNO before they can effectively take advantage of CBRS small cell RAN for mobile offload. Also, Mobile Experts believe that the cable operators will harden their Core EPC before earnestly ramping up small cell RAN deployment. By 2024, the cable operator spending on CBRS radio equipment will rise to above $200M annually, representing about 25% of the total. Finally, the CBRS radio equipment spending by enterprises and neutral host providers will make up about 26% of the total at about $220M in 2024. Private LTE and in-building wireless applications will drive CBRS investments by the enterprise segment. The overall CBRS radio equipment market is expected to reach over $850M in 2024, growing at a triple-digit CAGR.

CBRS Infrastructure Forecast

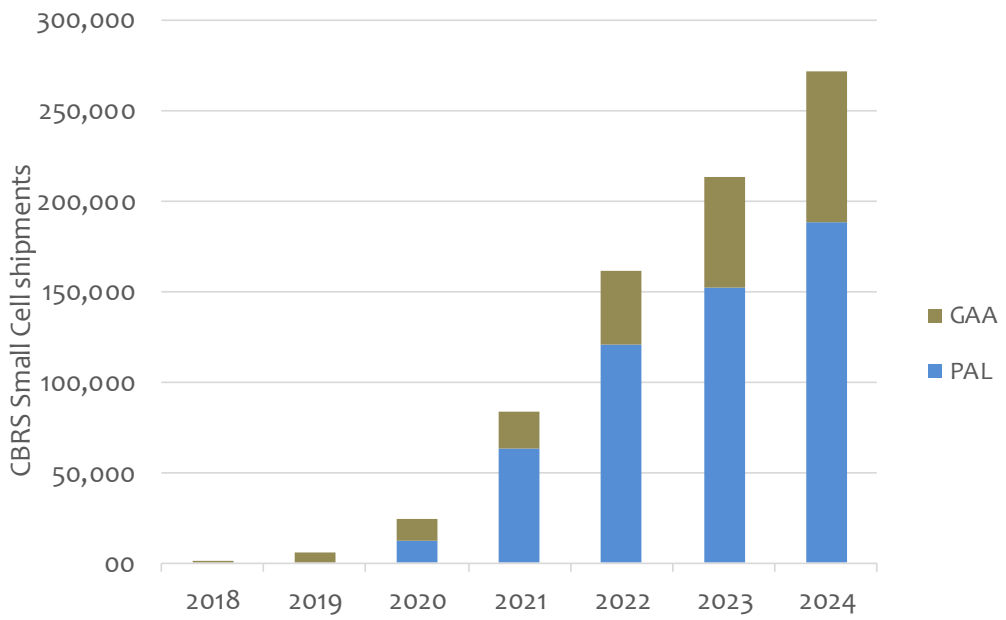
Heading into 2020, full commercialization of CBRS has not started. Mobile Experts had expected the CBRS full commercialization to have started during the third quarter of this year with active cable operator deployment of strand-mount small cells by now. Although the CBRS ICD launch in September of this year has brought more certainty around eventual commercialization of the band, we have noticed less enthusiasm for MVNO offload using CBRS by the cable operators. While we believe this is less to do with technical aspects of CBRS infrastructure and more around commercial agreement with an MVNO host mobile operator, the declining cable operator interest has significantly impacted our revised forecast. Mobile Experts expects the CBRS small cell unit shipments that grow ten fold from less than 25k units in 2020 to over 270k units in 2024.



Source: Mobile Experts

Chart 9: CBRS Small Cell Shipment Forecast by Indoor vs. Outdoor, 2018-2024

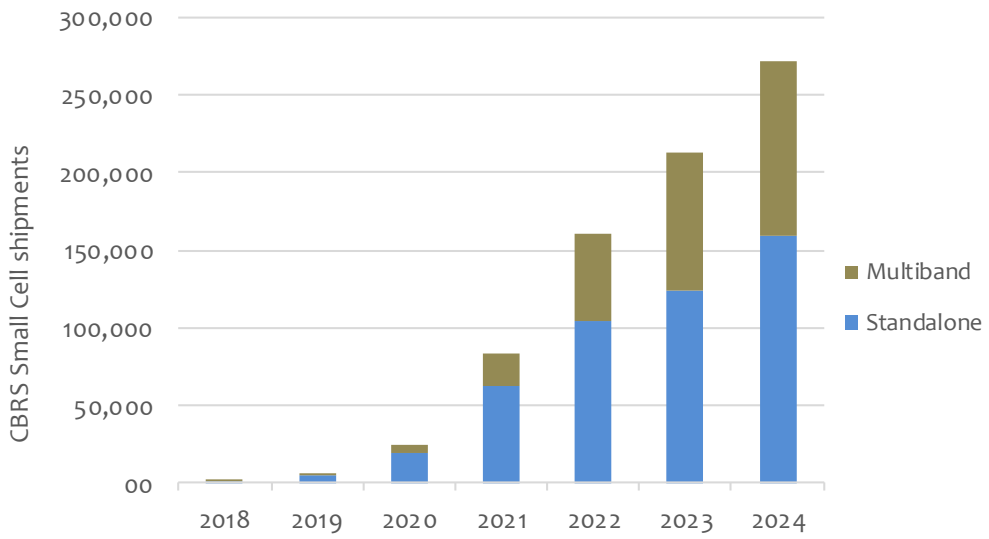
A majority of initial CBRS infrastructure deployments will be outdoor small cells. Major telco and cable operators, as well as WISPs, will deploy outdoor CBRS access points for fixed wireless use. Also, some mobile operators like Verizon will use CBRS outdoor access points deployed as remote radio heads to aggregate licensed carriers along with CBRS bands to increase network capacity. While the outdoor unit shipments will eventually plateau at a steady volume, the indoor access points will ramp up starting 2021 as enterprises deploy private LTE systems using the CBRS band. During 2023-2024, neutral host providers will also ramp up indoor access point deployments at certain "middleprise" venues for in-building wireless applications. Mobile Experts projects the number of indoor small cell shipments to outpace the outdoor units in 2023 as private LTE and in-building wireless use cases drive enterprise-driven deployments.



Source: Mobile Experts

Chart 10: CBRS Small Cell Deployment by License Type, 2018-2024

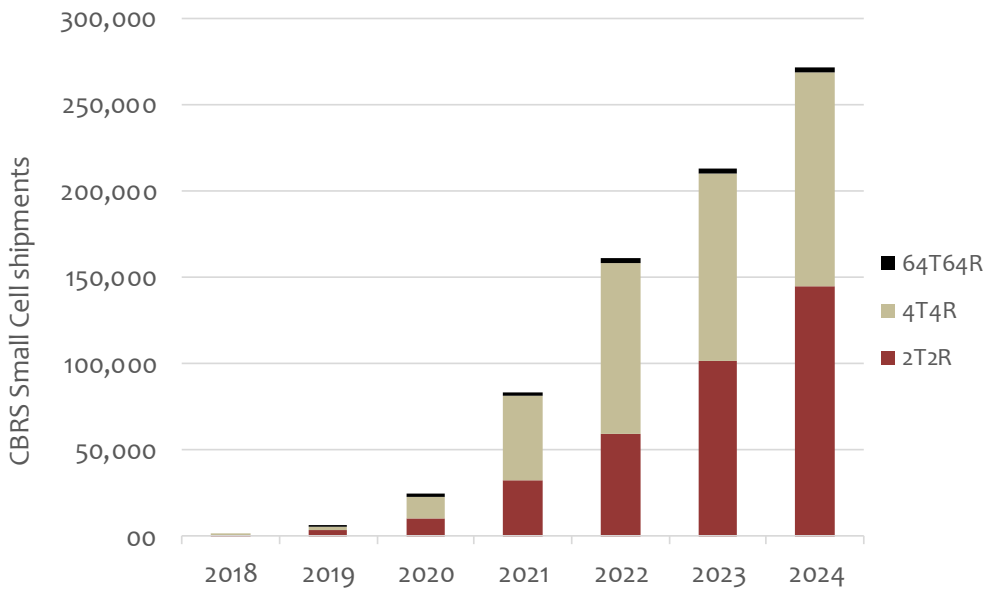
Mobile operators' penchant for licensed spectrum is, of course, not a surprise. They prefer exclusive use of licensed spectrum for control and barrier to entry against the competition. Barring out-right exclusive use, the PAL license in a shared CBRS spectrum model is the next best thing. The PAL licensing arrangement provides priority access to the CBRS spectrum most of the time. In contrast, the GAA use can potentially bring unknown quality issues associated with the "unlicensed" shared use. Hence, Mobile Experts expect major mobile and cable operators to bid for PAL licenses and will operate CBRS radio infrastructure under PAL licenses as soon as they become available. Thus, the CBRS small cell deployments under PAL will dominate those operating under GAA. While WISPs in rural areas and many private LTE networks will operate under GAA where the probability of incumbent or PAL use is minimal, they will be fewer relative to the majority of CBRS infrastructure leveraging PAL.



Source: Mobile Experts

Chart 11: CBRS Small Cell Shipment Forecast by Multiband vs. Standalone, 2018-2024

Mobile Experts expect a majority of mobile operator CBRS deployments will leverage multiband small cells, i.e., units that support both licensed and CBRS bands. This type of CBRS small cells allows the operators to leverage the CBRS band as secondary carriers in carrier aggregation to boost network capacity and peak user speeds, similar to LAA. On the other hand, most of the cable operators and enterprise private LTE deployments will use control and data channels in the CBRS band. With proliferation LTE networks using CBRS band by new entrants like cable operators, WISPs, and enterprises, the standalone CBRS small cell deployments will outpace multiband deployments of the mobile operators.



Source: Mobile Experts

Chart 12: CBRS Small Cell Shipment Forecast by MIMO order, 2018-2024

The CBRS radio infrastructure products will have a broad range of features in terms of power limits, antenna configurations, etc. For major telco fixed wireless applications, we see massive MIMO radios (64T64R) in concert with a higher MIMO antenna configuration on CPEs to maximize coverage and data speeds. For mobility applications, we see 4T4R as a popular choice to increase network capacity in working with popular smartphones in the market. 5G operation in the 3.5 GHz band will drive 4x4 MIMO implementation, so we expect smartphones to support CBRS with 4x4 MIMO as well. A clear trend over the long term is the 4x4 MIMO small cell infrastructure.

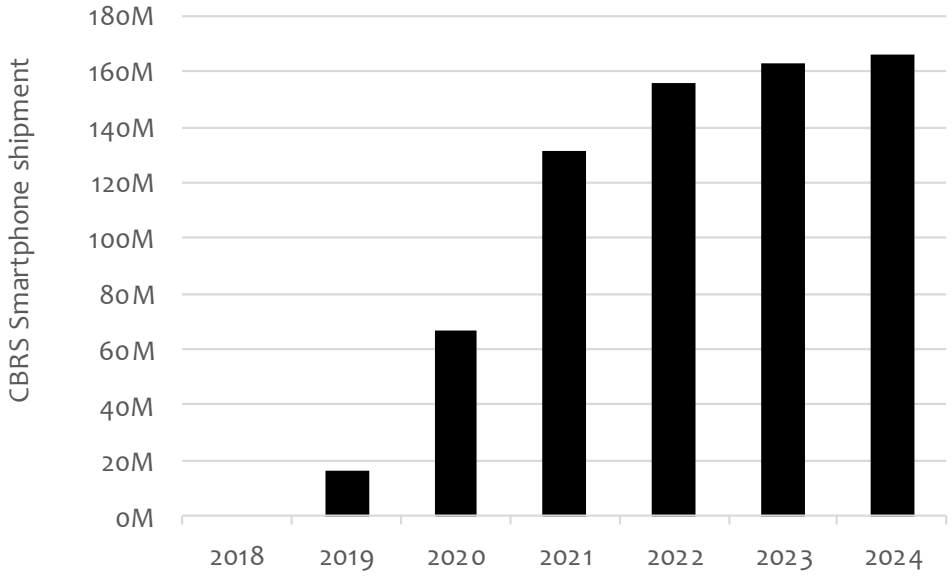
CBRS End Devices Forecast

While the higher-value infrastructure CBSD equipment dominates the overall CBRS equipment market, the end device market will drive higher volume growth in the future especially as the private LTE market takes hold. Growth in private LTE networks and an increasing number of use cases at certain enterprise segments will accelerate the proliferation of IoT devices. Mobile Experts envisions three categories of CBRS end devices:

1. Smartphones for mobile use;
2. Broadband CPEs for fixed wireless or mobile offload; and,
3. IoT devices for private LTE use

Smartphones, of course, will dominate with mobile applications driving a major portion of CBRS infrastructure investment by both mobile and cable operators. As predicted, we saw

major tier-one smartphones supporting the CBRS band 48 coming to the U.S. market in the second half of 2019. The iPhone 11 launch in September this year was a big catalyst for the market and set the stage for widespread adoption of the CBRS band on future smartphones coming to the market. By 2021-2022, we expect majority of high-end and mid-tier smartphones to support this band, with about 150M smartphones sold annually. In other words, practically every LTE smartphone sold in the USA will include CBRS by 2024.

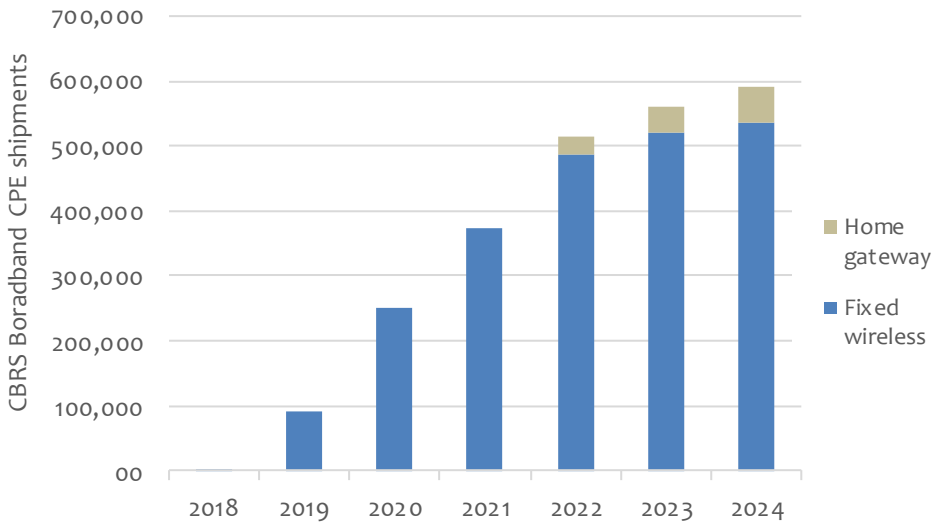


Source: Mobile Experts

Chart 13: CBRS-enabled USA Smartphone Shipment Forecast, 2018-2024

Considering an expected rise of CBRS-enabled smartphones in service over the next 2-3 years, we expect this to create new business opportunities in the in-building wireless space; thus, creating a virtuous cycle of further CBRS infrastructure investment in some venues. The dual-SIM, dual-connectivity feature on top-tier smartphones is expected to play a significant role in private LTE and neutral-host in-building wireless services. Corporate employees and multi-tenant subscribers can use dual-SIM smartphones to access both private LTE coverage indoors while accessing normal operator coverage everywhere else.

While far fewer in unit shipments, non-handset terminals, including broadband CPEs and IoT devices will grow quickly. IoT devices will be used in Private LTE applications, growing to hundreds of thousands of units per year by 2022, eventually growing to about 700k units by 2024. Also, CBRS fixed wireless access will involve hundreds of thousands of CPEs customer premise equipment (CPEs) to enable fixed wireless broadband access.

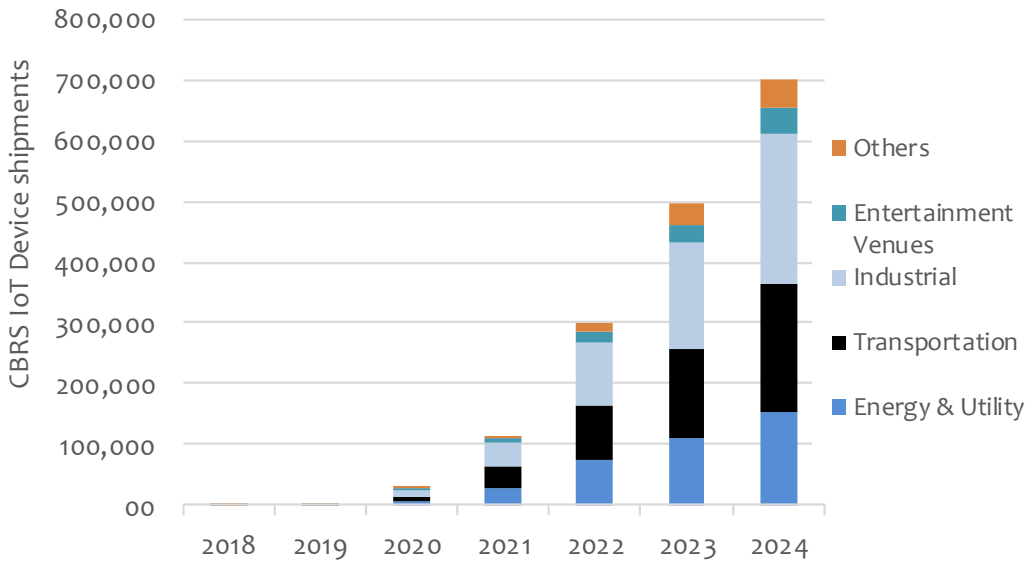


Source: Mobile Experts

Chart 14: CBRS Broadband CPE shipment, 2018-2024

The CBRS fixed wireless CPE deployment is expected to ramp up quickly as tens of thousands of legacy Part 90 devices[16] already in service are expected to be upgraded to CBRS Part 96. By our estimate, there are about 100k "legacy" fixed wireless CPEs that operate in Part 90. We are aware that about 80% of these can be upgraded to Part 96 (CBRS) through FCC grant authorization. Although these legacy units are already in service, we account for them as if they are "shipped" in our shipment forecast above. In addition to the fixed wireless CPEs, we also account for the possibility of home gateway CPEs embedded with CBRS radios for mobile traffic offload. These home gateways can be especially useful for cable operators who can use these residential CBRS small cells to offload mobile traffic. With some uncertainty around cable operators' mobile strategy, we have assigned a low probability of the cable operators adopting home gateways. Hence, our home gateway forecast is set low.

[16] The legacy fixed wireless devices operating in an upper portion of the CBRS band (3.65-3.70 GHz) operate under Part 90 rules. Part 96 refers to the CBRS rules. Hence, the legacy Part 90 devices need to upgrade to Part 96 by April 2020 deadline set under the CBRS rule.



Source: Mobile Experts

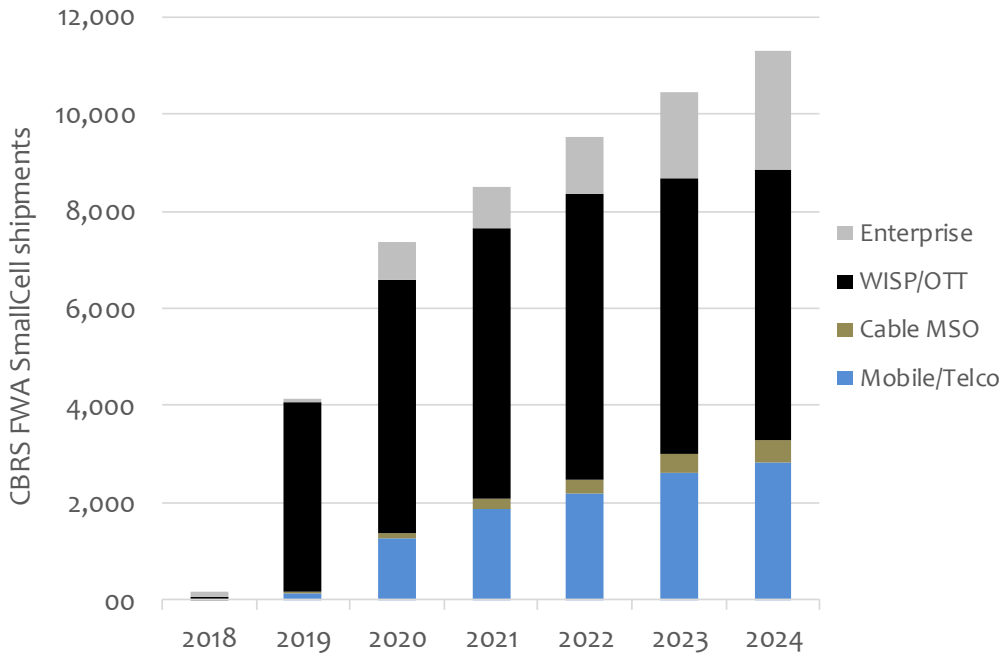
Chart 15: CBRS private LTE end device shipment by industry, 2018-2024

IoT devices are a bit more tricky as multiple different market segments will drive the use of Private LTE. One of the biggest drivers today in industrial and transportation applications is the use of surveillance cameras to stream video feeds. The video cameras are used for security, or for safety in heavy industrial operations with cranes and robots moving around. We see healthy level of interest among heavy industries in Transportation (airports and shipping ports), Utility, Oil & Gas, Mining, Industrial (manufacturing, warehousing), Agriculture, etc. A common theme among these enterprise segments is that they are looking for private LTE solutions to provide secure and reliable wireless connectivity for mission-critical applications.

CBRS Equipment Forecast for Fixed Wireless Access

The 150 MHz of the new CBRS spectrum offers additional spectrum resources for wireless operators of all types. One of the key use cases identified for this potentially affordable spectrum is fixed wireless access. Some WISPs already use the upper portion of the CBRS band (3.65 – 3.70 GHz) for this purpose. The fact that the lower portion (3.55 – 3.65 GHz) of the band will be available, and possibly with higher-priority access with PAL licenses, is a boon for WISPs looking to add capacity to their strained networks. Additionally, some mobile/telco and cable operators see CBRS as potentially lower-cost spectrum option to extend 25/3 (downlink/uplink) and 100/10 Mbps broadband coverage as part of their CAF commitments. Besides fixed wireless broadband services, some enterprises see CBRS as a

good option for fixed wireless alternative to wired connections to data devices such as video cameras or other IoT sensors.



Source: Mobile Experts

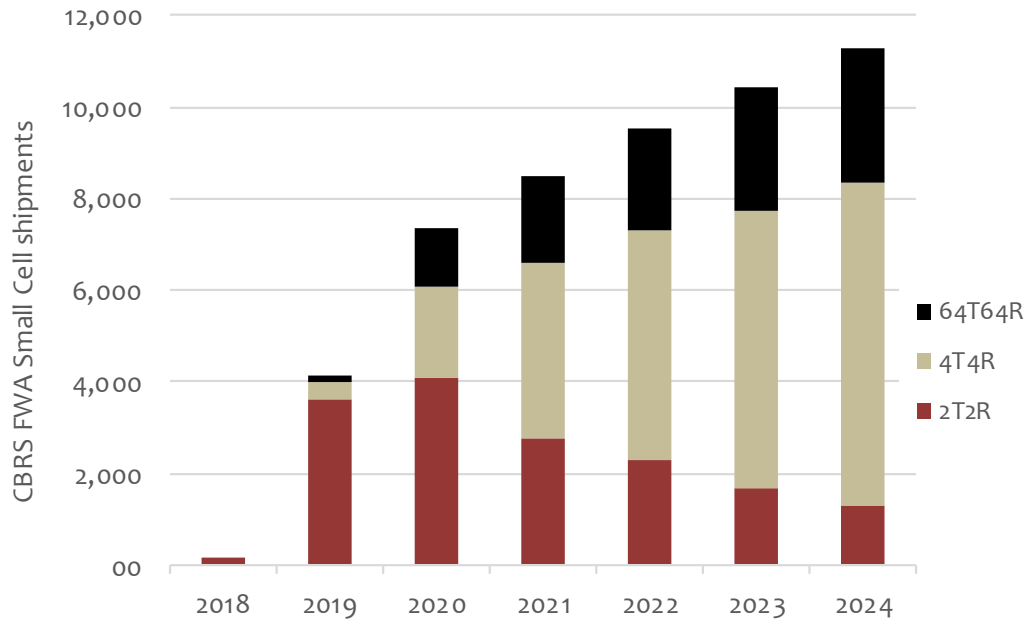
Chart 16: CBRS FWA Small Cell Shipment by Operator Type, 2018-2024

WISPs will be early adopters of CBRS small cell infrastructure deployments for fixed wireless applications. They are already the incumbent players of CBRS fixed wireless application. Under the legacy, Part 90 rules, many WISPs, and some industrial enterprises operate fixed wireless services in the 3.65 – 3.70 GHz band. Although a CBRS full commercialization has not commenced yet, we have accounted several thousand legacy Part 90 access points as "CBRS" units since many of them have been granted Part 96 authorization. About 8000 - 10,000 legacy Part 90 access points are expected to be upgraded to Part 96 over the next 12 months. Mobile Experts expect a majority of WISPs will opportunistically deploy CBRS access points under GAA as only large WISPs will likely bid for PAL licenses under the final rules that generally favor large players with capital to invest in spectrum.

Over the next several years, Mobile Experts view large mobile and telco operators as major players in CBRS fixed wireless deployments. Several major mobile and telco operators are expected to deploy fixed wireless networks to meet their CAF commitments. For example, AT&T has announced its plan to deploy CBRS infrastructure on over 1000 sites across multiple states to meet its CAF commitment. Several other telco operators are also evaluating CBRS infrastructure and are expected to announce their plans in 2020. The number of CBRS fixed wireless access points deployed by mobile/telco operators will rise

steadily from about 1,200 units in 2020 to over 2,800 units in 2024 as the number of telcos deploying fixed wireless networks increases. In addition to the mobile/telco operators, the cable operators, especially those serving in rural/suburban markets are showing interest in extending their cable broadband footprint via wireless. For example, MidCo, a regional cable operator serving Minnesota, S. Dakota, and N. Dakotas, has been trialing CBRS gears in the field. Charter, the second-largest cable operator, has also expressed renewed interest in extending its DOCSIS cable footprint via CBRS.[17] While the cable operators have been publicly vocal about their fixed wireless plans via CBRS, we expect the actual fixed wireless deployments by the cable operators to be minimal in scope.

Besides the fixed wireless broadband expansion, enterprise private LTE deployments will be another key driver of CBRS fixed access infrastructure. Many enterprises are keenly interested in CBRS networks to provide wireless connectivity solutions for mission-critical applications such as security cameras and other IoT sensor networks that require reliable and secure connectivity solution besides Wi-Fi.



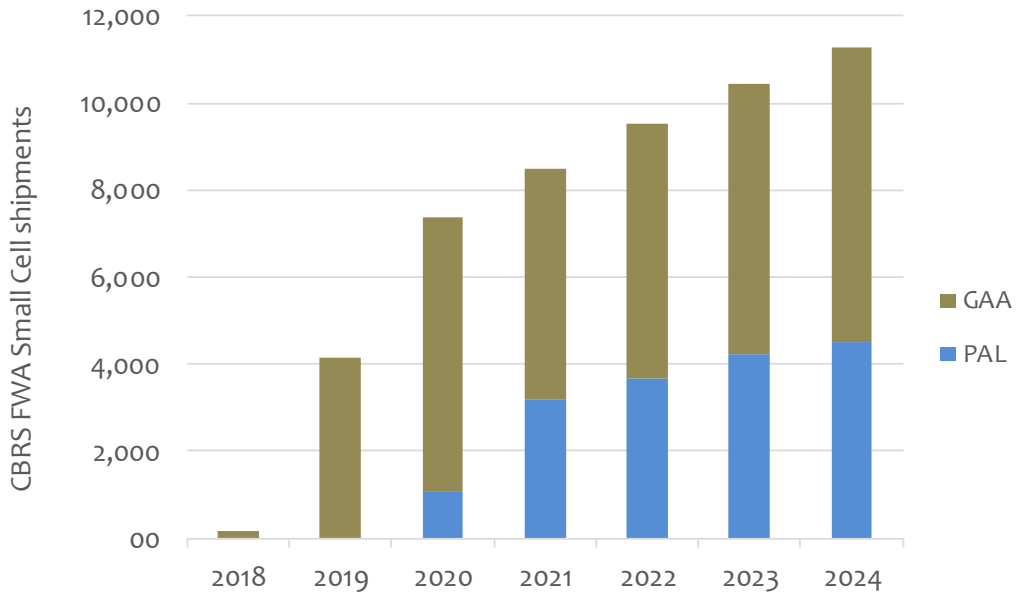
Source: Mobile Experts

Chart 17: CBRS FWA Small Cell Shipment by MIMO Order, 2018-2024

Most fixed wireless CBRS small cells will use 2x2 MIMO at first, but we expect these to quickly migrate to 4x4 MIMO because antenna size or similar considerations do not constrain the CPEs. In some instances, massive MIMO configurations like 64T64R will drive some fixed wireless deployments to both extend coverage and increase network capacity.

[17] https://www.multichannel.com/news/charter-readies-fixed-cbrs-deployment

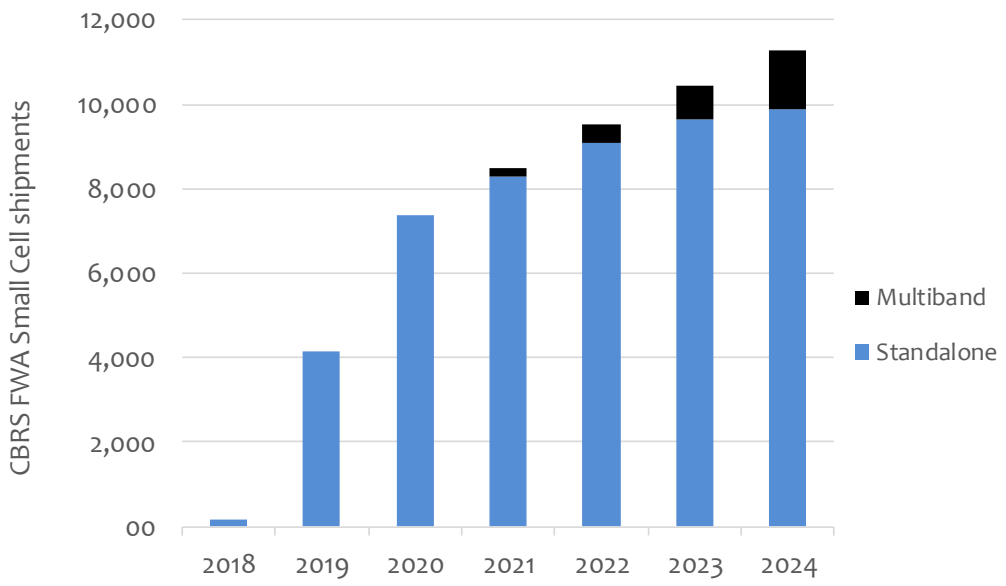
By employing higher antenna diversity on CPEs, coverage reach and data speeds can be extended. For example, a CPE with 2T8R antenna configuration along with massive MIMO access point can increase link budget.



Source: Mobile Experts

Chart 18: CBRS FWA Small Cell Deployment, GAA vs. PAL, 2018-2024

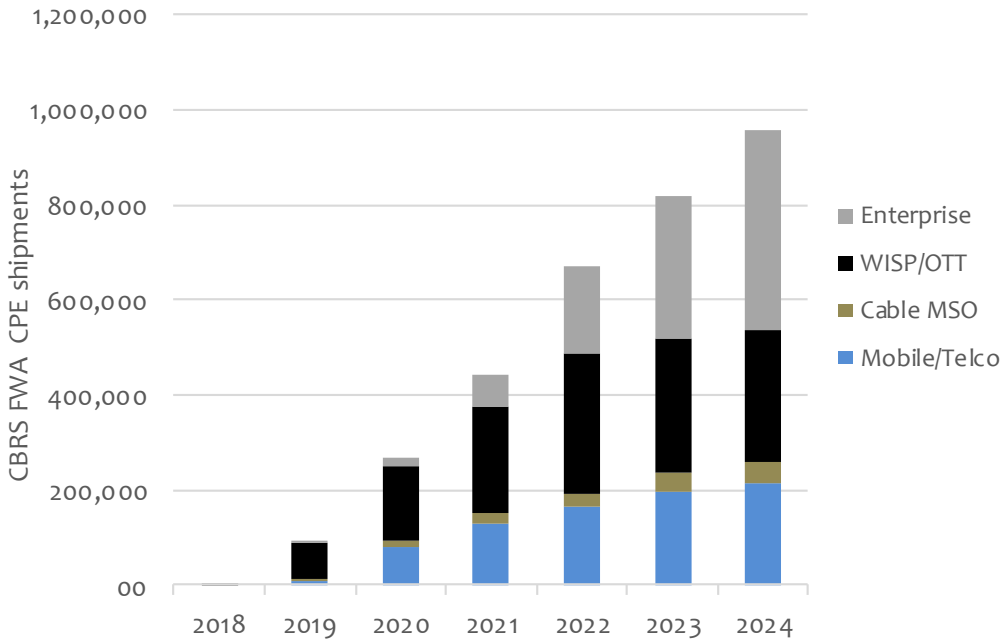
The final CBRS rules that extend PAL licensing to ten years with renewal and geographic licensing areas based on county size generally favor larger players since each PAL license is expected to cost higher than smaller "chunks" based on census tracts and shorter 3-year duration. Hence, Mobile Experts predicts that major mobile and cable operators will likely deploy CBRS infrastructure under PAL while the majority of smaller WISPs and enterprises will opt for GAA deployment. Some large WISPs and enterprises may be inclined to participate in the PAL auction, but we expect this group to be small in number. In most cases, rural WISPs will deploy CBRS infrastructure under GAA with a hope that PAL licensees won't deploy radio infrastructure in their markets. Since a major portion of fixed wireless deployments will be in rural areas, we expect the majority (60-80%) of fixed wireless CBRS infrastructure deployments to be operating under GAA from 2020 – 2024.



Source: Mobile Experts

Chart 19: CBRS FWA Small Cell Deployment, Standalone vs. Multiband, 2018-2024

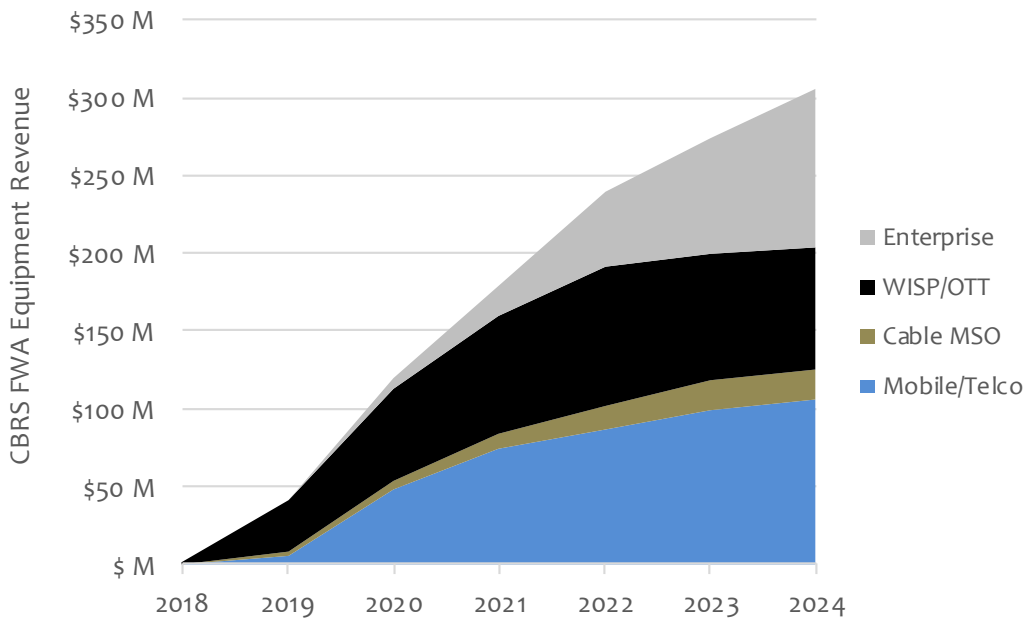
Most fixed wireless infrastructure deployments by WISPs and enterprises will be stand-alone small cells. In most instances, WISPs and enterprises deploy access points dedicated to a particular band (e.g., 5 GHz access point, 2.5 GHz access point, etc.). While we expect some mobile operator deployments may utilize multi-band access points for carrier aggregation or integrated radio units to make deployments easier, most of these fixed wireless applications call for simple solutions.



Source: Mobile Experts

Chart 20: CBRS FWA CPE Shipment by Operator Type, 2018-2024

The fixed wireless CPE shipments closely track small cell infrastructure (access point) shipment. As clearly shown above, in terms of fixed wireless end device shipments, the enterprise segment dominates as the increasing number of use cases for enterprise private LTE networks is expected to grow the number of end devices during 2022-2024 significantly. Besides the simple cellular-to-ethernet bridge and other fixed gateways/routers, we expect to see many cost-optimized "bridging" devices like USB dongles and modules to connect many more fixed data devices such as video cameras within a growing number of private LTE networks. For carrier-driven fixed wireless networks, the number of broadband CPE shipments will closely track the fixed wireless access point shipments. Within this carrier segment, the CPE unit growth for the major mobile operators will be higher than smaller WISPs as they will likely attract subscribers faster than smaller WISPs with higher marketing and brand recognition in most markets.



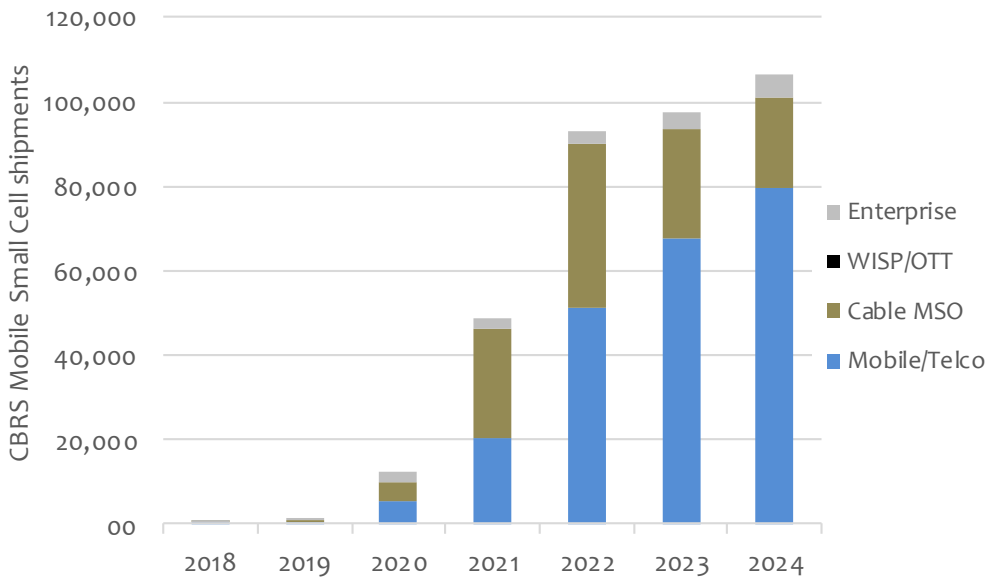
Source: Mobile Experts

Chart 21: CBRS Equipment Spend by Operator Type, for Fixed Wireless, 2018-2024

The CBRS radio equipment market for fixed wireless, deployed by operators (for fixed wireless broadband) and by enterprises (for private LTE), is expected to steadily grow from less than $50M in 2019 to over $850M in 2024. The carrier-driven fixed wireless service will drive the initial deployments, especially by the mobile/telco operators, who will steadily grow their spend. WISPs will be steady spenders of CBRS fixed wireless equipment including small cell infrastructure and subscriber CPEs. During 2022 – 2024, the enterprise-driven fixed wireless applications will drive the growth in overall spend as the CBRS equipment spending for fixed wireless broadband services taper off.

CBRS Equipment Forecast for Mobile Access

The CBRS rules based on larger licensing areas and longer-term licensing duration favor a longer-term investment in the band. Major operators would be more inclined to invest in CBRS infrastructure knowing that the capital expenditure towards the new spectrum will be protected from possible interference from GAA users if they were to operate under PAL. With this assurance, Mobile Experts believe that mobility use, or more plainly, increasing network capacity, will be the primary application that drives CBRS infrastructure investment by both mobile and cable operators.



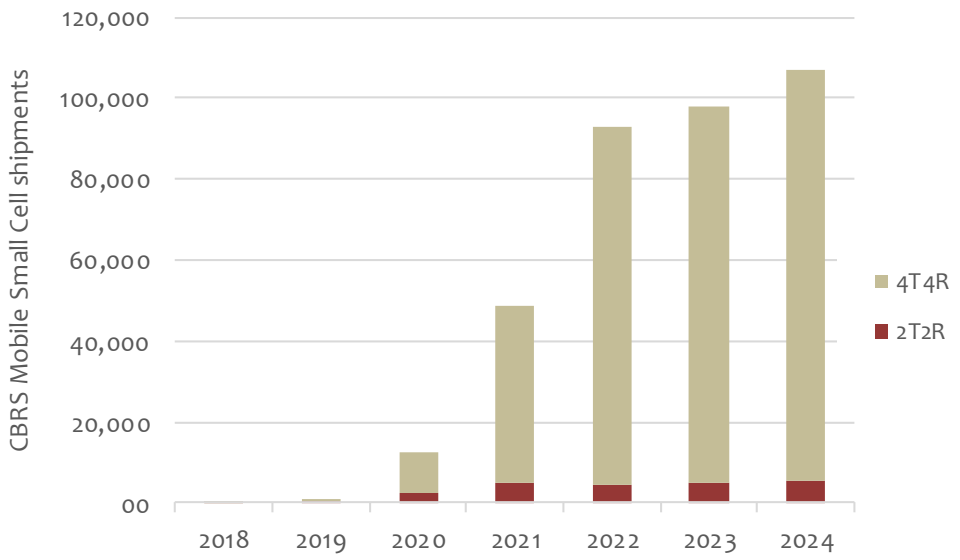
Source: Mobile Experts

Chart 22: CBRS Mobile Small Cell Shipment by Operator Type, 2018-2024

The mobile operator's interest in CBRS deployment for mobile use differs by carrier. Verizon has the least amount of licensed spectrum among the four major mobile operators. Hence, we believe it will immediately adopt CBRS small cells in its network plans. We are aware of Verizon bringing its installed base of CBRS small cells online. While AT&T's current plan for CBRS for mobile use is unknown, we believe it will eventually adopt CBRS use for mobility sometime during 2021-2022. Meanwhile, T-Mobile may also adopt CBRS in its small cell layer if its planned merger with Sprint falls through. Our forecast currently does not include T-Mobile adopting CBRS. We believe T-Mobile is on track to focus its Macro and small cell network deployments centered on the 2.5 GHz band.

For cable operators, the outdoor mobile deployment of CBRS presents a new challenge in setting up a truly mobile network that can seamlessly handoff mobile traffic between MVNO host network and owned CBRS or Wi-Fi network. In this year's report, we have reduced the cable operator deployment of CBRS infrastructure for mobile offload to reduce MVNO "rent" costs. Our revised outlook is largely based on our belief that cable operators will first focus on their Core EPC development to take advantage of mobile traffic offload onto owned CBRS small cell networks. Until then, the cable operators will depend on a host network operator's Core EPC – which translates into commercial agreement to direct traffic away from host operator's RAN to owned CBRS network. For these reasons, we have pushed back the cable operator ramp of CBRS infrastructure for mobile use out to 2021. In addition, we now project a relatively low volume shipments of CBRS small cells during the 2022-2024 period.

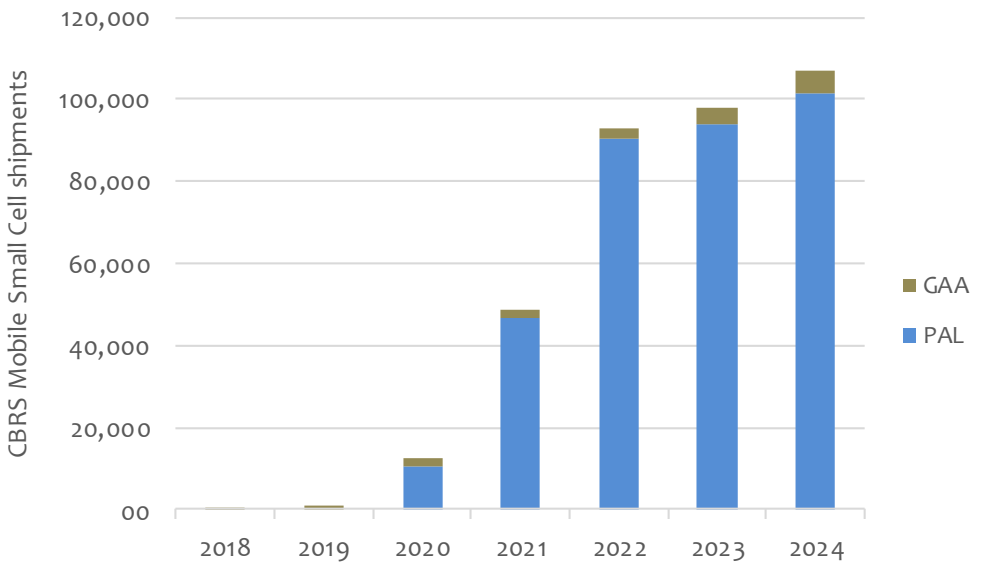
Mobile Experts envisions private LTE deployments for autonomous and portable IoT devices. While we expect these enterprise "mobile" scenarios to contribute to the overall mobile CBRS infrastructure forecast (Chart 22), this enterprise-driven segment will be much smaller in comparison to the carrier mobile broadband use case involving hundreds of millions of smartphones.



Source: Mobile Experts

Chart 23: CBRS Mobile Small Cell Shipment by MIMO Order, 2018-2024

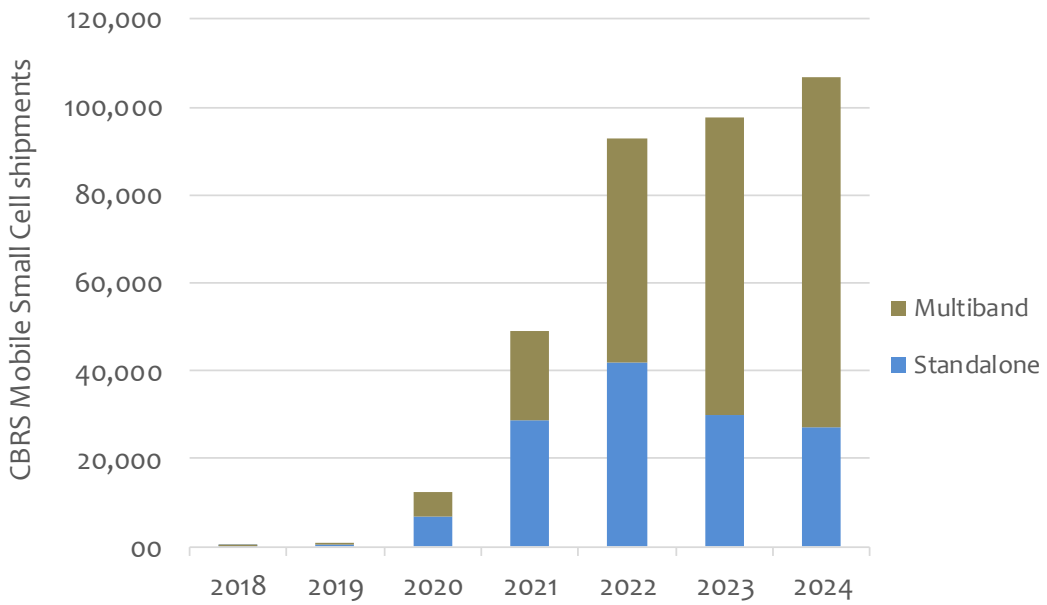
The 4x4 MIMO configuration will dominate the CBRS infrastructure dedicated to mobility application. Smartphones are getting increasingly sophisticated and capable. As user expectation of data throughput capacity on devices continues to go up, the 4x4 MIMO configuration is increasingly commonplace. Today's LTE macro layer is mostly 4x4 MIMO to handle higher throughput capacity, and major portions of outdoor CBRS small cells are also expected to support 4x4 MIMO.



Source: Mobile Experts

Chart 24: CBRS Mobile Small Cell Deployment, GAA vs. PAL, 2018-2024

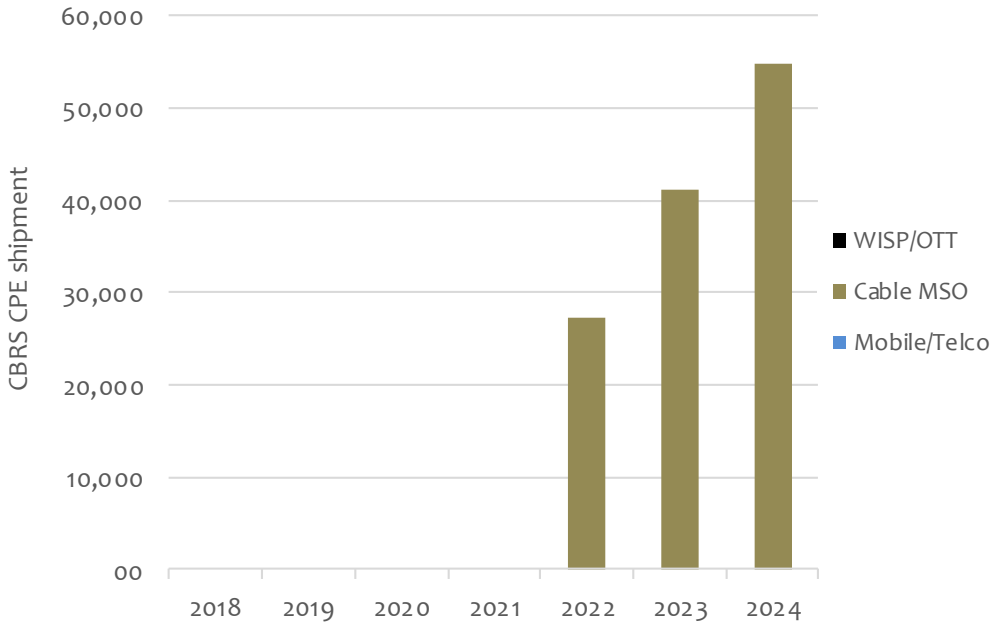
Overwhelming importance that major operators place on service quality will drive the majority of CBRS radio infrastructure dedicated to mobility to operate under PAL. While the initial deployments before 2020 operate under GAA by rule, most major operator deployments will operate under PAL as we expect that major operators will acquire PAL licenses in most major markets. Some will opportunistically aggregate bands across both PAL and GAA to increase throughput capacity.



Source: Mobile Experts

Chart 25: CBRS Mobile Small Cell Deployment, Standalone vs. Multiband, 2018-2024

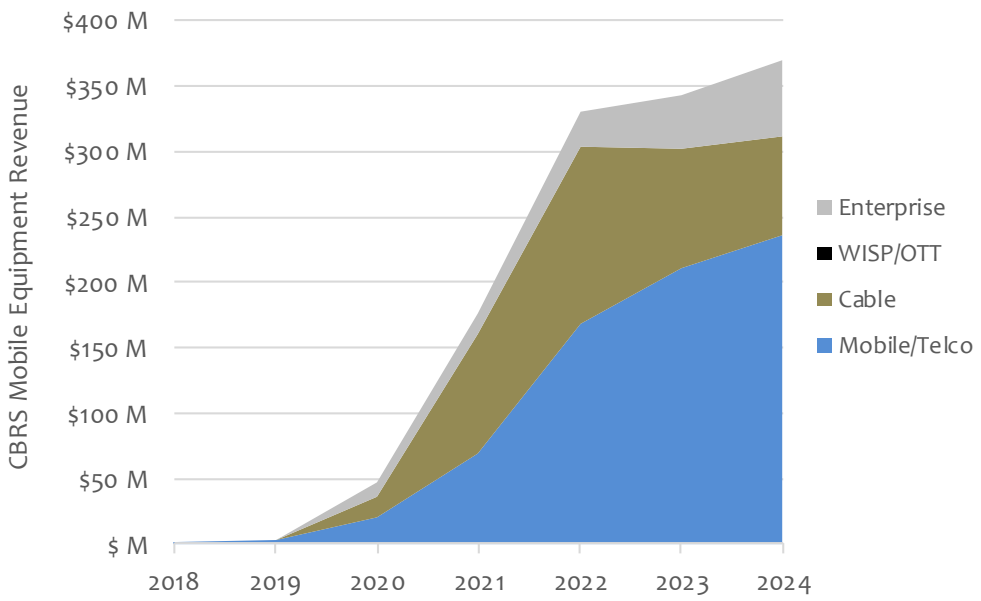
Mobile operators will be the dominant stakeholders in deploying CBRS infrastructure for the mobility use case (see Chart 22), and the primary use of CBRS will be carrier aggregation of a licensed band along with CBRS bands as secondary carriers to increase the capacity of data channels. Because of this, the mobile operator deployments will involve multi-band small cells. Mobile Experts believes that multiband small cell deployments will increase over time as a natural migration of small cell layer to increase network capacity through carrier aggregation across multiple bands across both licensed and shared/unlicensed spectrum including CBRS.



Source: Mobile Experts

Chart 26: CBRS Mobile CPE Shipment by Operator Type, 2018-2024

While we normally think of smartphones as end user devices in mobility scenarios, we have categorized home broadband gateway products with embedded CBRS radios as potential CPE end devices that can be used for mobility use cases. Cable operators can leverage CBRS-enabled home broadband CPEs as a mobile offload network at home instead of Wi-Fi for instance. While we expect this residential "inside out" wireless network to be less than likely, the above forecast is to reflect this possibility, especially among cable operators. For example, Comcast has been vocal about leveraging its 19M Wi-Fi hotspots, most of which are based on Wi-Fi embedded in home gateways. Instead of Wi-Fi, Comcast can just as easily broadcast CBRS signals off of home gateways in the future.



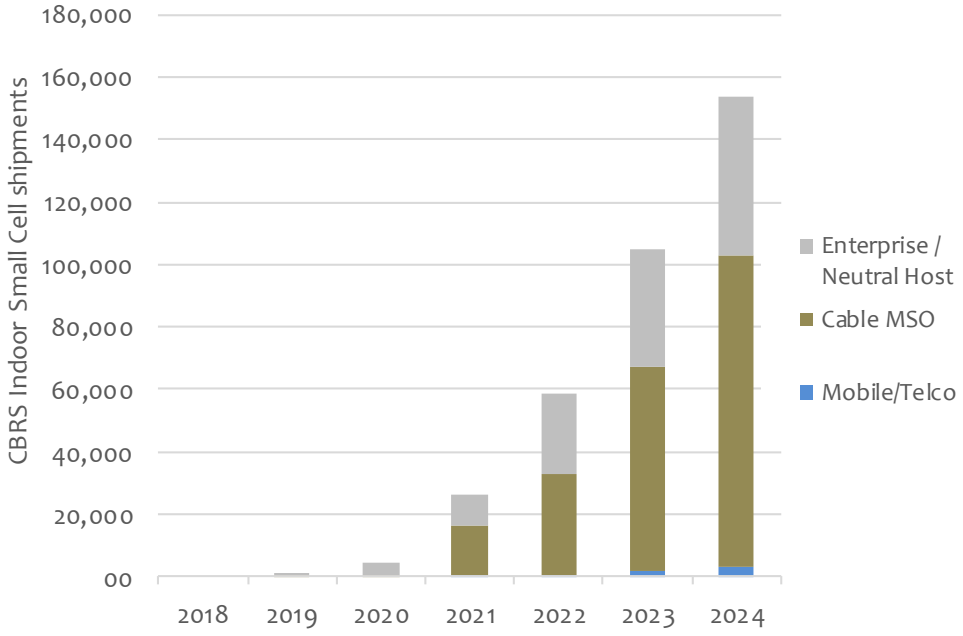
Source: Mobile Experts

Chart 27: CBRS Equipment Spend by Operator Type, for Mobility,2018-2024

The mobility application represents the biggest driver of CBRS equipment revenue. The outdoor portion, as shown above, is expected to rise from less than $50M in 2020 to almost $400M in 2024. While this sum is not hugely significant compared with tens of billions of dollars in network CAPEX that operators spend each year, it shouldn't be ignored. We see a broad interest among both large and small vendors introducing CBRS radios. A great deal of this revenue opportunity can be captured by aggressive players like Airspan, Commscope/Ruckus, Corning/Spidercloud, and others.

CBRS Equipment Forecast for Indoor Access

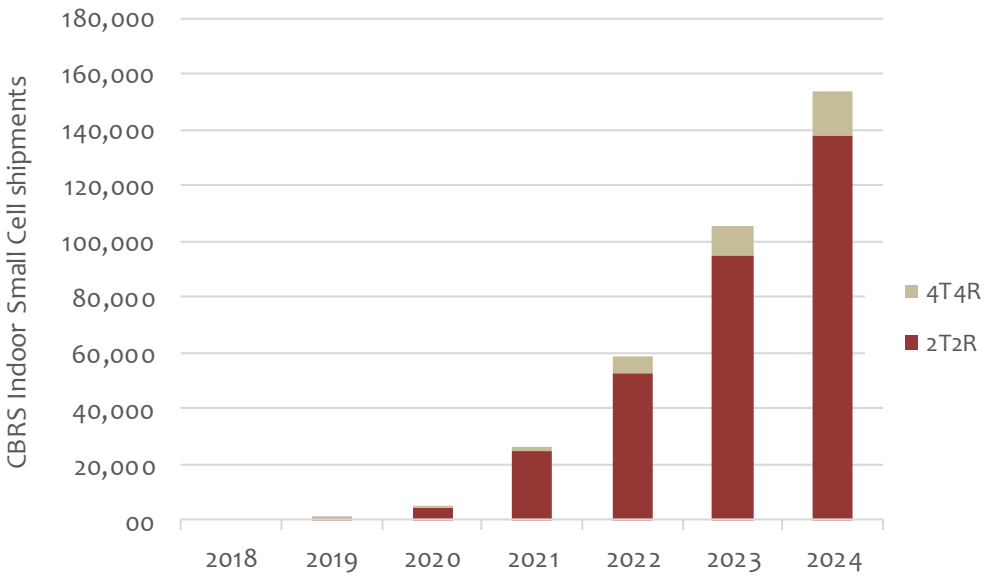
While outdoor small cells will be the primary network layer for a mobile offload or capacity augmentation, indoor small cells can be effective "inside out" mobile network layer. In other words, the outdoor CBRS equipment outlook presented in the previous section, along with indoor CBRS equipment market outlook presented in this section constitute overall market dedicated for mobility use case.



Source: Mobile Experts

Chart 28: CBRS Indoor Small Cell Shipment by Operator Type, 2018-2024

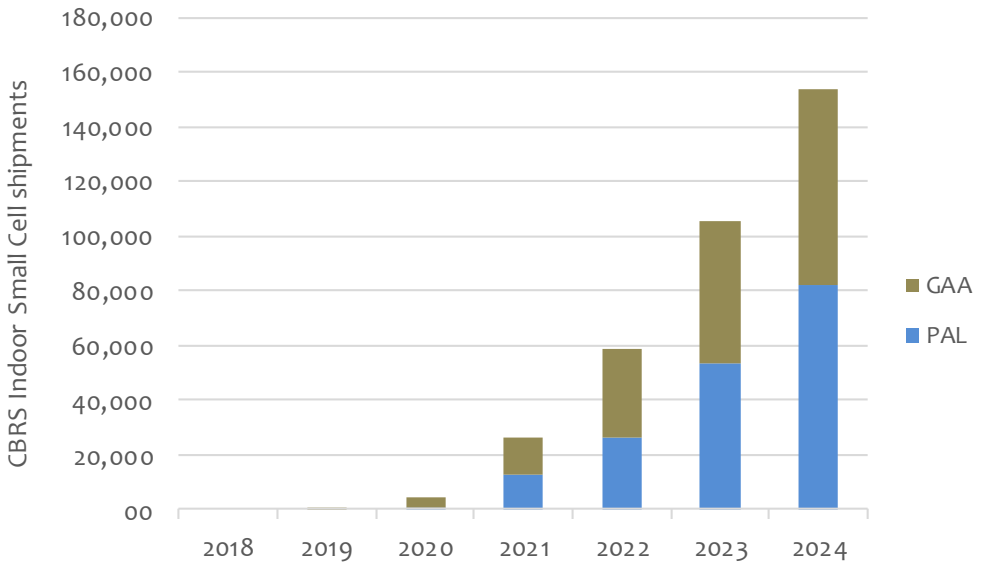
Indoor deployment of CBRS radios by mobile operators will be very small as the mobile operators will primarily look to their ongoing outdoor small cell deployments to add the CBRS capacity layer. However, we expect significant growth from cable operators in the indoor segment as they have a strong broadband footprint. With the recent upgrade to DOCSIS 3.1, we see the strong potential of the cable operators leveraging their large fixed broadband footprint to add mobile network layer. Here, the cable operators can selectively deploy indoor CBRS small cells to create "inside-out" mobile network to offload mobile traffic.



Source: Mobile Experts

Chart 29: CBRS Indoor Small Cell Shipment by MIMO Order, 2018-2024

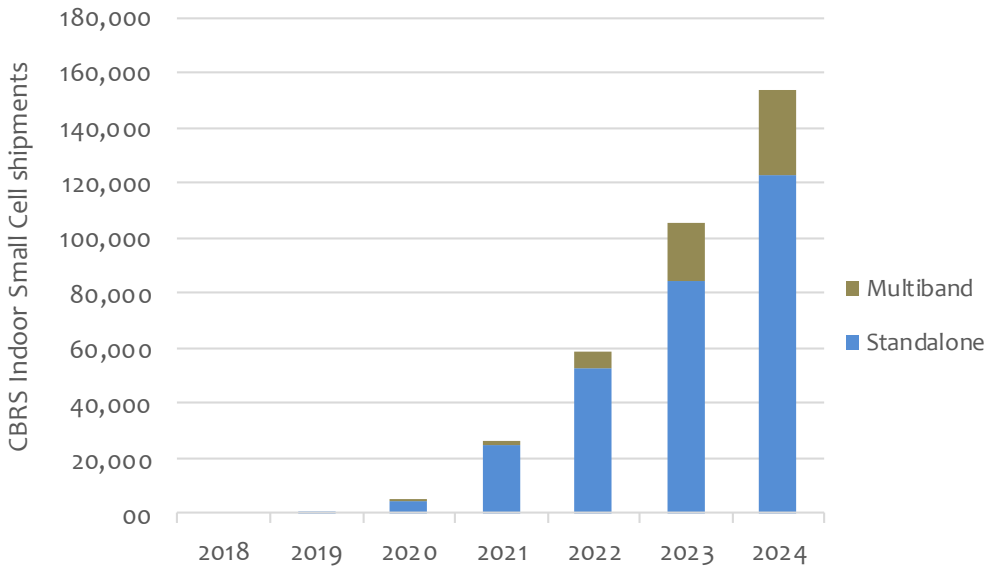
Since a major portion of indoor small cell deployments will be at medium size venues, the user capacity won't be that high. Thus, 2x2 MIMO configuration will be sufficient to handle expected data throughput and user capacity handling in most cases. Moreover, the indoor segment is more price-sensitive, so keeping the products simple will help drive down the cost of the units.



Source: Mobile Experts

Chart 30: CBRS Indoor Small Cell Deployment, GAA vs. PAL, 2018-2024

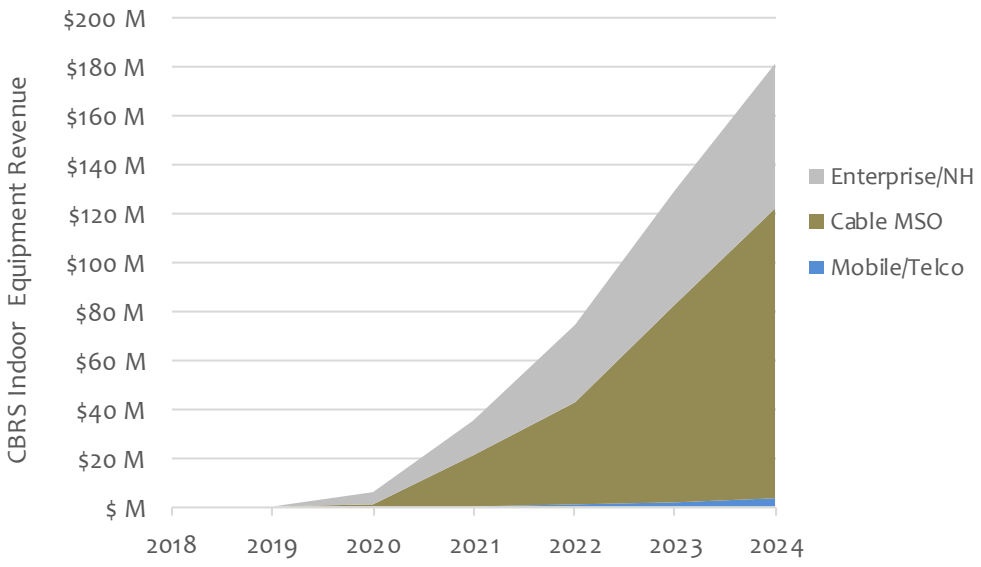
Besides the operator-driven indoor deployments, most enterprise-driven indoor deployments will likely operate under GAA. Through careful RF planning using tools such as iBwave and RANplan, enterprises can optimize their RF coverage to mostly indoors. While we expect some large industrial private LTE outdoor deployments to operate under PAL, we expect these to be fewer in number. Meanwhile, most operator-driven indoor deployments will largely operate under PAL as we expect major operators to secure PAL licenses next year. Assuming that the cable operators will secure PAL licenses, our forecast shows a higher share of PAL use in the later years of our forecast period.



Source: Mobile Experts

Chart 31: CBRS Indoor Small Cell Deployment, Standalone vs. Multiband, 2018-2024

Most indoor CBRS deployments will leverage standalone small cells, including all private LTE networks deployed by enterprises and the majority of cable operator deployments. In the later years, we expect some indoor deployments by cable operators and neutral host providers to involve leveraging multiband units to leverage both licensed spectrum from mobile operators and the CBRS band as a part of "infrastructure-sharing" type MVNO in which cable operators or neutral host operators take responsibility for deploying infrastructure and share the network capacity from that infrastructure with mobile operators. We believe this is the model that Altice has with Sprint in their MVNO agreement.



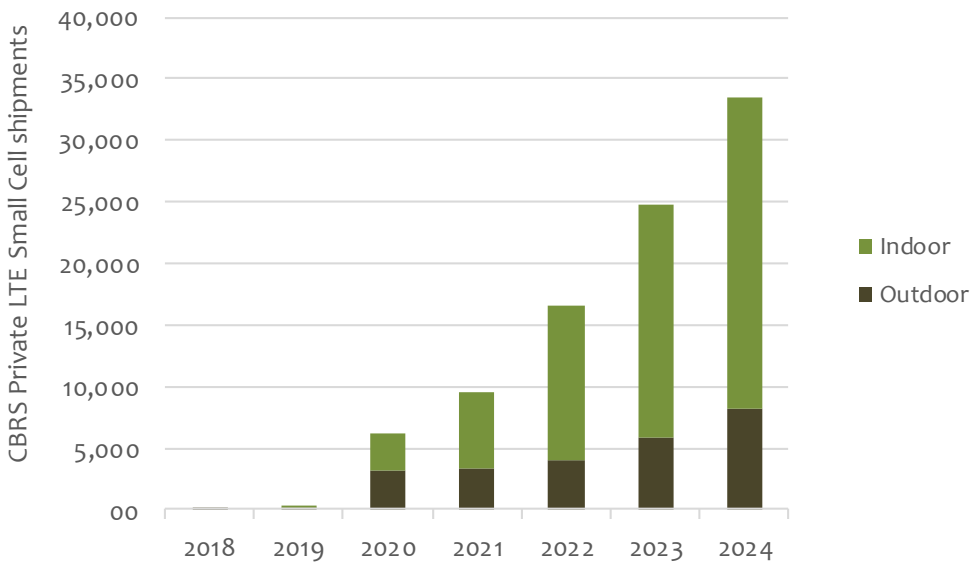
Source: Mobile Experts

Chart 32: CBRS Equipment Spend by Operator Type, for Indoor Applications,2018-2024

The spending on indoor CBRS small cells will be about half that of mobile outdoor infrastructure spend. The small cell unit volume is about the same, but since the average unit cost is less, the total spend comes to less than that of mobile outdoor infrastructure spend. Mobile Experts sees a strong ramp-up of the indoor CBRS segment, growing from about $1M in 2019 to over $180M in 2024. Enterprise-driven private LTE network deployments are expected to be a big contributor to this growth.

Private LTE Forecast

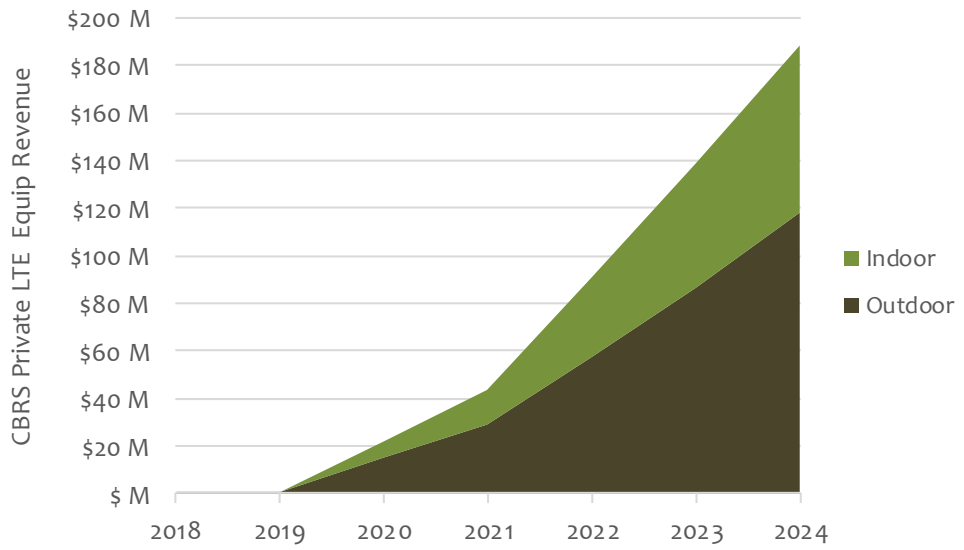
In the previous CBRS Indoor market segment, we combined Enterprise deployment with Neutral Hosts, because many enterprises will use Neutral Hosts to deploy their Private LTE networks. It may be difficult to distinguish between Private LTE and Neutral Host CBRS networks, as these systems could be set up for easy authentication and use by any smartphone that comes onto the CBRS networks.



Source: Mobile Experts

Chart 33: CBRS Private LTE Small Cell Shipment, Indoor vs. Outdoor, 2018-2024

To help in clarifying the market drivers behind deployment, we've isolated the deployments that are intended for truly private LTE use only. For instance, in port operations, asset tracking, industrial IoT, or corporate smartphone access within a private LTE network would be considered "private LTE-only" access. In contrast, a portion of CBRS indoor network deployed at a venue by a neutral host provider can be shared across both private LTE and in-building wireless or mobile offload use. Hence, the Private LTE shipment and revenue forecasts (Charts 33 and 34) in this section should not be added directly onto the Outdoor and Indoor CBRS market estimates. Private LTE use is already included in those Outdoor and Indoor CBRS market estimates. The initial CBRS indoor deployments will be driven by Private LTE applications. Over time, Mobile Experts projects that an increasing share of Indoor deployments to be shared across both Private LTE and public cellular use for a mobile offload or in-building cellular access.



Source: Mobile Experts

Chart 34: CBRS Equipment Revenue, for Private LTE only, 2018-2024

The CBRS equipment revenue dedicated to "private LTE-only" network deployments translates to about $180M in 2024, a split between outdoor (60%) and indoor (40%). Our view of the enterprise-driven private LTE market has improved since our last forecast. This is based on robust use cases that we see in the market. Mission-critical applications, especially in industrial settings (e.g., shipping ports, industrial warehousing, etc.), are driving the market demand for private LTE based on low-cost spectrum options. The enterprise-driven private LTE market is expected to be a meaningful contributor to the overall CBRS infrastructure market.

6 COMPANY PROFILES

Accelleran

Accelleran is a small cell OEM start-up based in Belgium focusing efforts to produce LTE TDD small cells, targeting both licensed CBRS bands for the U.S. market. The company first announced its CBRS small cell product at MWC 2017. The company has a few CBRS trials planned involving fixed wireless and private LTE applications. The company has a single-carrier and up to four-carrier multiband small cell products for the CBRS market.

ADRF

Based in Burbank, CA, ADRF manufactures in-building wireless solutions, including DAS, repeaters, and active and passive components. The company has strong direct relationships with Verizon and Sprint and has expanded its product portfolio with a modular and compact ADXV product line. The company also has a broad product portfolio of public safety systems, including digital repeaters covering the full breadth of public safety frequency bands across UHF, VHF, 700, and 800MHz. The company recently joined the O-RAN Alliance and CBRS Alliance, to expand its market opportunities beyond the core carrier in-building solutions market. The company announced the CBRS band support on its flagship DAS product, ADXV, for private LTE and IoT use cases.

Affirmed Networks

Founded in 2010, Affirmed Networks provides virtualized and cloud-native Core EPC software systems for mobile network operators. The company's virtualized EPC is involved in Syniverse's CBRS private LTE network at Syniverse's Innovation Lab. The company's virtualized, cloud-native mobile core solutions have been deployed at several Tier-1 operators around the globe.

Airspan

Airspan Networks has developed a line of LTE small cells, including indoor and outdoor units, with integrated wireless backhaul. The company has extensive experience in delivering enterprise-class and outdoor small cells to leading mobile operators around the globe including Sprint, Reliance Jio, and Rakuten. The company has CBRS-ready small cells to target both outdoor and indoor deployments. The company continues to expand its product portfolio ranging from indoor and outdoor radios that span sub-6GHz, millimeter wave, and several unlicensed bands for relay and backhaul.

Airwavz Solutions

Airwavz Solutions is a telecommunications infrastructure company serving both the commercial real estate industry and the major wireless carriers. The company designs, installs, owns, and operates wireless infrastructure inside commercial office and hospitality buildings in metropolitan areas. Airwavz is working with Globalstar whereby it will lease GlobalStar's band 53 (2.484 – 2.495 GHz) spectrum along with CBRS to provide a better SLA in in-building wireless services.

Altice USA

As one of the major cable operators in the U.S. with footprints in the NYC metro area and several states in the mid-section of the USA, the company provides cable broadband, pay-TV and now mobile (through Sprint MVNO) services to about 5 million residential and business customers across 21 states. As a part of the larger Altice Europe with leading mobile operations in France and other markets, the company has a lot of experience in mobile. The company struck an "infrastructure-sharing" MVNO deal with Sprint to start its aggressive mobile offering within its cable footprint. The company has conducted a few CBRS trials with leading radio vendors, including Ericsson, Nokia, Airspan, and Commscope (Ruckus).

Amdocs

Amdocs has built a sizable software and network engineering services business through acquisitions. It provides software automation solutions in network design, planning, integration, and optimization. With deep expertise in the Tier-1 network rollout, the company has developed SAS which is one of five SAS that has been approved by the FCC. The company is partnering with the ESC component.

American Tower

American Tower is a major wireless infrastructure provider with a global presence in North America, Europe, South America, India, and Africa. The company operates about 150,000 wireless communication sites globally. In addition to its primary business of operating over 40,000 cell towers in the United States, the company has more than 1300 buildings under management and provides in-building DAS and small cell services mainly at large venues such as stadiums, malls, casino resorts, and office buildings. With its core business of providing shared wireless infrastructure services, the company has strong relationships with all major operators and has a good growth prospect as a neutral host provider in the in-building space.

ANS (Advanced Network Services)

Advanced Network Services is a regional system integrator providing in-building wireless, tower, and other network infrastructure services in the northeast quarter of the USA and

along the east coast to enterprise customers and wireless and wireline operators. The company has offices in NY, PA, OH, IL. ANS was involved in the American Dream CBRS network deployment, where it led the systems integration work in partnership with JMA Wireless.

Athonet

Athonet is a mobile core specialist with a virtualized EPC solution offering that can be deployed through on-premise virtualized EPC or via public cloud like AWS. The company offers Core EPC services through AWS under the brand "BubbleCloud." It is involved in several CBRS private LTE deployments such as the Times Square and Angels Stadium deployments. The company's virtualized EPC solution is estimated to be involved in ~20 sites under STA and ICD licenses.

AT&T

As one of the largest integrated telecommunication and media companies in the U.S., AT&T has a multi-faceted approach to the use of CBRS. The company has announced that it will leverage CBRS in fixed wireless network launch over 1100 sites across 11 states. The company is deploying massive MIMO (64T64R) along with high-power CBSD Category B device as CPEs. Its CBRS plan for mobile use is not yet clear, but it is reasonable to expect that it would carrier aggregate CBRS channels along with its licensed carriers to opportunistically expand data channel capacity.

Baicells

Founded in 2014, Baicells is a privately-held company based in Beijing, China. The company's product solutions range from indoor and outdoor small cells, CPEs, and antennas. With a new sales office in the U.S., the company is expanding into the fixed wireless WISP market. The company has made a great stride taking a share in the U.S. fixed wireless market with its LTE-based fixed wireless solutions. It has CBRS-ready small cells and CPEs with cloud-based EPC solution that it offers as a monthly cloud service.

BEC Technologies

BEC Technologies is a manufacturer of wired & wireless IP networking solutions for mobile operators, residential, enterprise, and Industrial markets. BEC's product portfolio includes xDSL, FTTH, 3G, 4G/LTE, Fixed Data Routers, VoIP/VoLTE Gateways, rugged outdoor, industrial/M2M connectivity, Fleet/Telematics, and remote device management. The company's CBRS products include LTE IoT modem, enterprise gateway, indoor/outdoor routers.

Black Box

Black Box is a system integrator/solution provider that provides comprehensive wireless solutions including DAS, small cells, CBRS, Wi-Fi for various enterprises ranging from healthcare, retail, finance, manufacturing, and hospitality. Black Box acquired Inner Wireless in late 2012, and together they have focused on support of multimode DAS systems for enterprise applications.

Boingo Wireless

Boingo has transitioned from a Wi-Fi-centric neutral-host service provider mostly at airports to a major DAS player with over 35,000 DAS nodes in service. The company runs DAS, small cell, and Wi-Fi networks at airports, military bases, and other public venues. The company has expanded beyond its core airport venues to malls, hotels, and military bases now. With the company's recent acquisition of Elauwit Networks, Boingo is further expanding to multi-dwelling units in student housing and multifamily complexes. The long-term contracts with vertical segments allow the company to expand DAS, small cell, CBRS, and Wi-Fi networks into these markets

Cambium Networks

Cambium was formed in late 2011 after the original Motorola Canopy business was sold to private equity. Based in Rolling Meadows, IL, the company is one of the leaders in the fixed wireless space. Its PMP 450 platform is widely recognized as a "carrier-class" fixed wireless solution with an extensive installed base around the world. The company provides both point-to-point (PtP) and point-to-multipoint (PtMP) radio gears across a wide swath of spectrum bands, including 3.5 GHz, 5Ghz, and 2.5 GHz. The company is planning to introduce LTE fixed wireless gear called cnRanger for both the 2.5 GHz and CBRS bands. The company has a sizable installed base of 3.65 GHz PMP450 products in service which will need to be transitioned to Part 96 (CBRS).

Casa Systems

Headquartered in Andover, MA, Casa Systems was founded in 2003 with core business in cable broadband and video product solutions. The company has since expanded its product solution portfolio to include wireless products addressing carrier Wi-Fi and small cell products. With its core business in the cable industry, the company has been expanding into wireless with several outdoor and indoor small cell products including those supporting the CBRS band that can be strand-mounted. Also, its NetComm acquisition provides a foothold in fixed wireless CPE market.

Celona

Celona is a VC-funded company founded in April 2019 by a team of executives with a background in cellular wireless, enterprise networking, Wi-Fi, and cloud infrastructure. Celona's founding team members have been part of companies such as Qualcomm, Aruba, Cisco. Celona is working on a networking platform for private mobile networks powered by 4G/5G and enables business-critical apps in the enterprise to take advantage of the CBRS spectrum. Celona's solution architecture is designed to automate the deployment of cellular wireless by enterprise IT organizations and managed service providers and simplify its integration with an enterprise IT network.

Charter Communications

Charter is the second-largest cable operator in the USA, with over 26 million broadband household subscribers. Its cable network is expansive with a geographic footprint covering over 50 million households from east to west coasts. Since launching its mobile service through Verizon MVNO, Charter has attracted about 800,000 mobile subscribers. The company has been very active conducting multiple CBRS trials for mobility and fixed wireless use cases.

Cisco Systems

Cisco is the leading enterprise wireless networking supplier with over 50% of the Wi-Fi market share by our estimate. With its extensive channel partnerships, the company has partnerships to furnish CBRS/OnGo radio and the end-to-end LTE small cell solutions. While the company's radio strategy is still largely planted in Wi-Fi and IEEE 802.11 roadmap, it is also a major LTE and 5G EPC Core supplier in several key service provider accounts. As a sponsor member of the CBRS Alliance, it is believed that the company is involved in several trials and testing.

Comba Telecom

Comba holds a strong position in supporting coverage solutions in China, as well as a few South Asian and Latin American markets. The company supplies a wide range of repeaters, DAS, residential and indoor small cells, and fixed wireless CPEs. Comba has several key OEM supplier relationships.

Comcast

Comcast is the largest US cable operator with over 28M cable broadband household subscribers. The company has been moving aggressively in an expansion of its "Xfinity" Wi-Fi footprint touting 19 million hotspots. Although a majority of its public-facing hotspots are dual SSID from residential CPE's, the company has deployed outdoor units along its cable plant in strategic locations. Since its MVNO mobile service launch, the company has

attracted about 1.8 million mobile subscribers. It is partnering with Charter to develop mobile core EPC solutions jointly. While it has not been as public, it is believed that it has conducted several CBRS trials.

Commscope (Ruckus)

Commscope is a global leader in fiber connectivity and mobile solutions. With the ARRIS acquisition, the company's CBRS portfolio immediately increased with Ruckus enterprise solutions ranging from Wi-Fi and campus networking products. With combined assets across a diverse customer base that includes cable and mobile operators and enterprises, the company has the entire end-to-end solution, including SAS, small cells, enterprise networking solutions. Commscope's SAS is involved in AT&T's CBRS fixed wireless network deployments, and Ruckus is involved in about 50 private LTE trials.

Connectivity Wireless Solutions

With headquarter in Atlanta, GA, Connectivity Wireless has been involved in mid-size in-building wireless deployments primarily with DAS but sees opportunities in CBRS, LAA, small cell, and managed Wi-Fi deployments. With the recent acquisition by a private equity firm, the company is looking to expand its in-building wireless system integration business. The company has been involved in a couple of high-profile CBRS trials at Times Square and Angles Stadium performing several private LTE use cases.

Contour Networks

Contour Networks is a U.S. division of Japan Communications, Inc. (JCI), which was established in 1996 by Japan's Ministry of Communication to develop programmable SIM solution. Contour Networks has launched a USIM solution that allows enterprises to create customized SIM cards to simplify network authentication for LTE/CBRS networks. The USIM solution allows enterprises deploying and trialing CBRS networks.

Corning

Corning has extensive in-building wireless solutions, including its fiber-based digital DAS systems and Spidercloud small cell portfolio. Corning small cell solutions include multi-carrier units that can support the CBRS band. The company is focused on enterprise networks, using a centralized controller to coordinate clouds of licensed/unlicensed/shared LTE radio nodes attached via Ethernet LAN/WAN transport. Corning's CBRS small cell products are involved in several ICD trials, including Tier-1 indoor deployment and several private LTE applications in healthcare, mining, and manufacturing.

Cradlepoint

Based in Boise, Idaho, with offices in Silicon Valley, UK, and Australia, Cradlepoint provides wireless edge solutions for branch offices, mobile, and IoT networks. The company provides LTE and 5G modem/mobile router solutions to connect branch offices and edge enterprise networks. The company boasts more than 18,000 active enterprise and government organizations around the world, including 75 percent of the world's top retailers, 50 percent of the Fortune 100, and first responder agencies in 25 of the largest U.S. cities. Cradlepoint cellular-based modem solutions connect POS terminals, vehicles, and IoT devices. The company's mobile routers were integral part of connecting end devices to the CBRS networks including Hitachi cameras in the City of Chicago trials, American Dream Mall' CBRS private LTE network, and many others.

Crown Castle

Crown Castle is one of the major "tower" companies with a growing small cell infrastructure business. The company has made several fiber acquisitions to bolster its small cells business by offering both backhaul transport and site leases along those metro fiber routes for mobile operator customers to deploy small cells or outdoor DAS remote radio heads and for enterprise customers to bring buildings on-net. The company's wireless infrastructure consists of 40,000 towers and 17,000 route miles of fiber, and the company has tens of thousands of buildings on-net. The company's CBRS plan may reside in neutral-host in-building wireless opportunity, which will take a few years to materialize.

CTS (Communication Technology Services)

Founded in 1990, Communication Technology Services is a major DAS and in-building wireless system integrator with a national presence. With about 600 employees, the company competes against regional players. The company has been involved in indoor and outdoor wireless deployments, including DAS, small cells, public safety, and Wi-Fi. In addition to installation services, the company engages in maintenance and monitoring services – really encompassing the full suite of installation to maintenance services.

Druid Software

Based in Ireland, Druid Software provides enhanced packet core (EPC) solutions primarily targeting private LTE applications. The company's RESTful API's allow software developers to integrate EPC with enterprise applications easily. The company EPC solution is involved in over 10 CBRS ICD/STA trials including the well-publicized American Dream deployment and 7 Casino resort in the state of Washington.

Ericsson

As one of the leading radio vendors in the U.S. market, Ericsson has an extensive radio portfolio across all classes including small cells. Ericsson offers 2x2 and 4x4 outdoor CBRS small cells as well as Radio Dot solution for indoor deployments. Along with its dynamic spectrum sharing (DSS) features on its networks, it is believed that a Tier-1 operator like Verizon would leverage the CBRS small cell layer onto 5G with the DSS feature. Ericsson's CBRS small cells are approved and believed to be coming online in anticipation of full commercialization of the band.

Extenet Systems

Extenet Systems is a privately-held wireless infrastructure provider of distributed networks. As a part of Digital Bridge, the company designs, owns, and operates neutral-host outdoor and indoor networks leveraging multiple technologies including small cells, Wi-Fi, RRH, DAS, and other technologies on behalf of mobile operators and enterprise customers. The company has about 2000 CBRS outdoor sites on-air, under contract, or construction. Also, it has been involved in over ten private LTE trials at key vertical venues, including sports arena, convention centers, commercial buildings, and manufacturing sites.

Federated Wireless

Federated Wireless is one of the leading SAS providers and founding members of the CBRS ecosystem. The company has been expanding the CBRS market opportunities across multiple sectors, including those in fixed wireless, mobile broadband, private LTE, and edge computing. The company secured its Series C round to complete expansion, including ESC network buildout.

Frontier Communications

Frontier Communication is a tier-2 telco with numerous wireline connections, many of which were acquired from Verizon divestments, including FiOS footprints in Texas, Florida, and California. The company has confirmed that it is testing fixed wireless to address broadband connectivity to underserved areas. Frontier, like other tier-2 operators, who have received CAF funding to address broadband availability, are actively evaluating fixed wireless solutions.

Fujitsu

Fujitsu is one of the leading telecom infrastructure suppliers in Japan and has a long history of supplying RAN equipment to domestic carriers. The company has ICD trials underway involving fixed wireless and private LTE applications, targeting wireline operators, entertainment venues, and municipalities.

Geoverse (ATN International)

Geoverse is a subsidiary of ATN International, which also has ComNet division, which is concerned the largest wholesale roaming carrier. Geoverse was created with CBRS in mind to provide roaming solutions across disparate CBRS private networks and with public carriers. Geoverse has its Core EPC and edge solutions that integrate EPC, IMS, RAN, and gateway functionality to support tens of thousands of subscribers. The company has deployed DAS with CBRS layer at 7 Cedar Casino in the State of Washington and provides roaming service for the American Dream CBRS private LTE network.

Google

Google has been in the CBRS spectrum policy discussions since the beginning of CBRS ecosystem development. It has been a strong proponent of spectrum sharing and has been instrumental in coming up with many of the spectrum sharing framework. In addition to SAS services, the company provides online CPI training. The company has partnered with Commscope to develop ESC network jointly. At a recent WISP event, the company announced its SAS pricing of $2.25 per month per fixed wireless broadband user to promote market development.

Intel

As a key proponent and enabler of virtualized RAN, Intel continues to dominate the data center server chipset market with its Xeon class servers. In addition to its x86 CPU architecture, the company also provides FPGA accelerator solutions (based on its Altera acquisition many years back). The company is a big proponent of virtualized RAN, and open RAN movement fostering radio equipment vendors to utilize its Xeon chipset and RAN software stack as a reference point to build commercial products.

Ip.access

Ip.access has a long history in small cells, having been an early pioneer of 3G/LTE small cells for Tier-1 deployments. Recently, it has focused on several vertical markets including enterprise private networks, security & surveillance, transportation, and rural segments. It continues to ship residential femtocell products to operators in Europe and India, but the company's main focus is around private LTE markets where unique market requirements may provide higher-margin business opportunities. The company provides indoor CBRS small cell and an end device module for OEM integrators.

JMA Wireless

JMA Wireless, based in Liverpool, NY, is one of the leading DAS suppliers with a strong lineup of in-building wireless and antenna solutions. The company has been expanding wireless solution lineup with XRAN (virtualized RAN) and CellHub (radio unit) products. The

company provides CBRS-approved CellHub and has been involved in several ICD trials testing out private LTE applications at the American Dream and the Angels Stadium. Also, the company is working towards Multi-Access Edge Computing platform, creating a full stack of edge computing and wireless solution for enterprise private wireless networking markets.

Metaswitch

Metaswitch provides a cloud-native 5G Core software solution based on virtualized network functions. The company develops commercial and open-source software solutions. Metaswitch claims that its solutions power more than 1,000 service providers. Its Packet Core solution was recently showcased as a part of Microsoft Azure capabilities for supporting private LTE applications leveraging Ruckus access point on CBRS spectrum.

Microsoft

As one of the global leaders in cloud computing, Microsoft Azure has been expanding into edge computing and running private LTE applications using CBRS access points. The company has been partnering with several Tier-1 operators on edge computing applications in both private and public LTE and 5G networks.

MidCo

As a regional cable operator providing broadband and video services to rural subscribers in Minnesota, N. Dakota, and S. Dakota, the company has also embarked on testing CBRS for its fixed wireless plans. The company won CAF-II auction to provide fixed wireless services and has been actively testing CBRS network using Telrad gear.

Motorola Solutions

As a global leader in the mission-critical communications industry, Motorola Solutions unveiled its MOTOTRBO Nitro two-way push-to-talk product based on CBRS. It offers a complete solution ranging from access points, management system, core EPC, and two-way subscriber units. It has several private LTE trials with industrial enterprises and cities. It is also working on other data-centric subscriber units that can take full advantage of the CBRS spectrum.

Multitech

MultiTech is a 50-years-old, privately-owned company based in Minnesota. Over the past 10-15 years, the company has been manufacturing cellular-based data products. Over the past few years, the company has expanded into producing unlicensed wide-area network products, including LoRa. Leveraging that experience, the company has expanded into the private LTE space and has a few CBRS-ready products, including a cellular-to-ethernet bridge

IoT device to address "after-market" LTE connectivity, modem router, and will be introducing ruggedized USB dongle for industrial applications.

NetNumber

Founded in 2000, NetNumber provides signaling control solutions that enable operators to develop new services across its multi-generation technology platforms. The company provides Centralized Signaling and Routing Control solutions (e.g., HSS, HLR, etc.) to the telecommunications industry under its TITAN brand of servers. The company has been involved in private LTE space through a few projects in mining, public safety, and government sectors. The company introduced portable "all-in-one" radio infrastructure solutions targeting public safety government agencies, emergency backup for mobile operators, etc. CBRS ecosystem is seen as an extension of the company's private LTE business.

Nokia

Nokia is a strong RAN vendor with an end-to-end portfolio across wireline and wireless products. Nokia has been an early mover in small cells with the Alcatel-Lucent acquisition of a residential femtocell portfolio. The company also has a strong product line of outdoor and indoor small cells based on its chipset solution. The company has been an early leader of CBRS and MulteFire small cell solutions based on shared and unlicensed spectrum. The company has a growing Enterprise business with over 120 private LTE engagements to date.

Qualcomm

Qualcomm is a dominant chipset supplier to the mobile industry, including the small cell market. Since its acquisition of DesignArt, Qualcomm has been continuously investing in this segment to expand beyond its stronghold in the handset market to mobile infrastructure. By leveraging much of the research and development from the handset side, the company has been able to expeditiously and in close coordination, to introduce complementary small cell infrastructure system-on-chip (SoC) platforms, including a new generation of small cell SoC that supports LAA, CBRS, and 5G across both sub-6GHz and millimeter wave bands.

Qucell

Qucell is a subsidiary of Innowireless, based in Korea. It has been shipping 4G LTE small cells to multiple Tier-1 operators in Korea and elsewhere and is working to introduce 5G small cells in the domestic Korean market and beyond. The company recently acquired FCC approvals for CBSD Category A outdoor small cells supporting up to two carriers. The small cells are expected to be deployed in 2020 for fixed wireless applications. In addition to CBRS, the company has been active in MulteFire deployments in Japan.

Quortus

Based in the UK, Quortus has a long history of developing mobile core software systems since 2009. The company claims over 1500 core network solution deployments across diverse market segments, including private-LTE for industry and enterprise, non-terrestrial network edge extensions, and government/defense deployments. The company joined the CBRS Alliance and involved in a few private LTE CBRS trials.

Samsung

Besides being a global leader in smartphone handsets, Samsung has been gaining experience and gaining share over the years. The company has been deploying millions of residential femtocells in North America, Korea, Japan, and few other markets. Samsung has been a key infrastructure supplier for Reliance Jio's LTE and has gained some foothold in LTE macro markets in North America and has been a leading voice and product supplier in the 5G millimeter wave deployments. In CBRS, the company has been focusing on Tier-1 fixed wireless deployments and is expected to introduce CBRS small cell products targeting private LTE in the years to come.

SBA Communications

SBA has about 30 years of experience providing tower infrastructure to the wireless industry and is considered one of the major tower companies. In addition to the tower portfolio, the company has been strategically growing in-building wireless business through exclusive rights to key venues. The company has a dedicated team to build turnkey systems, and finance those projects, in "high-value" targets, including campuses, stadiums and arenas, healthcare facilities, commercial office space, transportation hubs, and key outdoor venues. As a part of strategically growing other infrastructure businesses besides tower, the company has strategic investments and projects in CBRS and edge computing areas.

Sercomm

Based in Taiwan, Sercomm supplies residential and enterprise small cells as well as Wi-Fi routers in several regions. The company has taken the obvious step of integrating their Wi-Fi router and femtocell products. The company has CBRS-approved small cells and has been involved in several cable operators' CBRS trials. The company also provides CBRS-ready CPEs and IoT devices.

Sierra Wireless

Headquartered in Canada, Sierra Wireless is considered a leader in IoT. The company provides embedded and networking solutions ranging from modems, modules, fixed and mobile gateways, and routers. Also, the company provides cloud services related to data

analytics and insight. The company provides a couple of CBRS-ready modules. In addition, it is working on releasing ruggedized mobile router and gateway products.

Sky Connect Networks

A joint venture between Neutral Connect Networks and Sky Packets to address the smart city networks using Wi-Fi, DAS, Small Cells, including CBRS. The company is involved in CBRS network deployment at Times Square along with Federated, Ruckus, Athonet.

SOLiD

Headquartered in Korea, SOLiD has a strong market share in the DAS market. The company has been expanding into O-RAN and CBRS markets to expand its market opportunity away from traditional multi-operator DAS market. The company has patented WDM fiber solutions, which give them an advantage in fiber efficiency, especially for complex DAS installations. The company has announced its GENESIS platform in addition to its Alliance DAS solutions. It is developing several 5G indoor products which will be announced later this year or early next year

Sony

Sony is a global conglomerate with businesses in media, mobile communications, audio/video electronics, IT services, and even biotechnology. Sony is one of the approved SAS providers, but not much is known about its involvement in CBRS ICD trials. Mobile Experts believes that its SAS service may be involved in using private LTE applications at its studios and possibly other select private wireless networking projects.

Telit

Telit is one of the leading IoT and cellular module vendors. In 2018, the company announced its first CBRS module. The adapter card was UE category 18 device that was probably an overkill in most IoT applications. The company is expected to introduce more cost-optimized, lower UE category, modules and devices that support the CBRS band 48 in the coming years.

Telrad

Telrad offers LTE fixed wireless base stations for WISPs in the 2.5 and 3.5 GHz bands. It signed an agreement with Federated Wireless to extend the operation of its LTE base stations in the CBRS band. The company touts software-defined radio capabilities from its Alvarion acquisition. The Telrad parent company based in Israel has other businesses related to telecom. The company touts distributed EPC that is embedded as a part of its radio infrastructure so that the operators don't have to stand up a separate EPC.

Vapor IO

Vapor IO is building a neutral-hosted cloud by delivering a suite of hardware and software for edge computing and operating edge colocation services. The company's technology enables highly-distributed micro data centers to be embedded in the wireless and wireline infrastructure, colocated with the last mile or Radio Access Network and meshed together with software and high-speed fiber as part of the company's Kinetic Edge, technical architecture for city-scale edge computing. Vapor IO has partnered with Federated Wireless to leverage the company's MEC solution offering along with CBRS radio networks for private LTE applications.

Verizon

As the largest mobile operator in the U.S. with close to 130 million mobile connections, Verizon has been one of the leading operators in the CBRS Alliance. Leveraging the CBRS spectrum as a secondary data carrier, the operator can aggregate the ancillary data channels along with its licensed carrier to boost network capacity wherever it has CBRS small cells deployed. Similar to the way AT&T has leveraged LAA along with its LTE-advanced upgrade for "5G Evolution" upgrade, Verizon will be able to opportunistically increase network capacity through the carrier aggregation of CBRS bands. Verizon is believed to be bringing its CBRS-ready small cells online.

Vivint

Based in Utah, Vivint is a major smart home/security service provider. The company offers home security monitoring, video security, and other types of smart home automation services. The company's annual sales reach $700-800M. The company had built out fixed wireless networks in Salt Lake City and a couple of cities in Texas. It is currently exploring new technology and spectrum options, including CBRS, to extend its fixed wireless business.

Zinwave

Zinwave provides fiber-based DAS systems that can support cellular and public safety bands from 150MHz up to 2700MHz. The company has traditionally focused on public safety and enterprise segments across some key verticals including healthcare, hospitality, and commercial real estate. Headquartered in Dallas, the company still maintains its research and development office in the UK and is active in the CBRS Alliance. The company plans to support the CBRS band with its DAS systems to target enterprise in-building market.

7 ACRONYMS

2G: Second Generation Cellular

3G: Third Generation Cellular

3GPP: Third Generation Partnership Project

4G: Fourth Generation Cellular

5G: Fifth Generation Cellular

802.11: An umbrella standard that encompasses multiple unlicensed communications standards within the IEEE.

802.11a/b/g: Early generations of the 802.11 standard.

802.11n: The current generation of the 802.11 standard.

802.11ac: The generation of the 802.11 standard introduced in 2013.

802.11ax: A future IEEE standard for very high throughput in Wi-Fi.

AAA: Authentication, Authorization, and Accounting (typically refers to the server which performs these functions).

ACLR: Adjacent Channel Leakage Power Ratio (amount of power leaking into adjacent channels).

AP: Access Point (often referring to Wi-Fi access point)

APN: Access Point Name

ARPU: Average Revenue Per User

BSC: Base Station Controller

BTS: Base Transceiver Station

CA: Carrier Aggregation

CAF: Connect America Fund

CAF-II: Connect America Fund Phase II

CBRS: Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US

CBSD: Citizen Broadband Radio Service Device

CPE: Customer Premise Equipment (e.g., cable modem, broadband gateway)

dBm: Decibels of power relative to 1mW

DoD: Department of Defense

DRS: Distributed Radio System

DSL: Digital Subscriber Line

EAP: Extensible Authentication Protocol.

EAP-AKA: EAP via Authentication and Key Agreement.

EAP-SIM: EAP via Subscriber ID Module.

EAP-TLS: EAP via Transport Layer Security.

EAP-TTLS: EAP via Tunneled Transport Layer Security.

EIRP: Effective Isotropic Radiated Power

EMEA: Europe, Middle East, and Africa

eNB: eNodeB, or the radio access node for LTE

EPC: Evolved Packet Core.

ESC: Environmental Sensing Capability (sensor network to detect radars)

ePDG: Evolved Packet Data Gateway.

FCC: Federal Communications Commission

FTTP: Fiber to the Premise

GAA: General Authorized Access, applicable for the 3.5GHz shared spectrum, the lowest priority access, similar to unlicensed spectrum use

GB: Gigabyte

Gbps/km2: Gigabits per second per square kilometer

GHz: Gigahertz

HetNet: Heterogeneous Network

HLR: Home Location Register.

HSPA: High-Speed Packet Access

HSPA+: A subsequent evolution of HSPA with higher throughput

HSS: Home Subscriber Server

Hz: Hertz (cycles per second)

IEEE: Institute of Electrical and Electronics Engineers

IP: Internet Protocol

IPSec: Internet Protocol Security

I-WLAN: Interworking for Wireless Local Area Networks.

LAN: Local Access Network

LTE-A: LTE Advanced, a higher bandwidth version of LTE

LAA: LTE-License Assisted Access, a 3GPP-compliant "official" LTE-U technology

LTE: Long Term Evolution, a "4G" radio interface based on orthogonal frequency division multiplexed data

LTE-U: LTE-Unlicensed, an "unofficial" technology to run LTE waveform on 5GHz unlicensed spectrum band

MHz: Megahertz

MIMO: Multiple Input, Multiple Output

MNO: Mobile Network Operator

MSO: Multi-Service (or System) Operator (reference to a cable operator)

MVNO: Mobile Virtual Network Operator

MulteFire: Standalone LTE-U technology whereby both control and data plane traffic flows in an unlicensed band

MU-MIMO: Multi-User MIMO.

NGH: Next Generation Hotspot (Hotspot 2.0)

NHN: Neutral Host Network

NTIA: National Telecommunications and Information Administration (coordinates spectrum use by federal agencies)

OEM: Original Equipment Manufacturer

OFDM: Orthogonal Frequency Division Multiplexed

PAL: Priority Access License, applicable for the 3.5GHz band, second highest priority in use of the 3.5GHz shared spectrum

PAMid: PA Module Integrated Duplexer (RF frontend module containing PA, SAW duplexer, switch, transmitter low-pass filter, and receiver SAW filter)

PEA: Partial Economic Area

PSD: Power Spectral Density

QoS: Quality of Service

RAN: Radio Access Network

RF: Radio Frequency

SAS: Spectrum Access System, a software system to coordinate spectrum sharing (although it can be applied across all shared spectrum, its use is primarily focused on 3.5GHz CBRS)

SIP: Session Initiation Protocol

SSID: Service Set Identification

TD-LTE: Time Domain-based Long Term Evolution

UE: User Equipment

VAR: Value Added Reseller

W: Watts

WCDMA: Wideband Code Domain Multiple Access, a 3G radio interface

Wi-Fi: Wireless Fidelity (802.11 data communications)

WISP: Wireless Internet Service Provider

WLAN: Wireless Local Area Network

8 METHODOLOGY

To create estimates and forecasts for the CBRS market, Mobile Experts relied on direct input from more than 30 industry sources, with many different mobile, cable, and ISP operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts has also spoken with more than 40 other companies in related business areas for Carrier Wi-Fi, LTE-U, and LTE business areas—providing some valuable cost estimates and background data for potential CBRS growth.

Mobile Experts built a "top-down" forecast based on direct input from mobile operators, cable operators, neutral host companies, and wireless Internet service providers (WISPs). Then, Mobile Experts built a "bottom-up" forecast through discussions with OEMs, software developers, and semiconductor suppliers in the supply chain. For this early market, financial disclosures were not useful, so we relied on our cost analysis to make predictions about the likely course of technology choices for each business model.

Private LTE deployment was considered as a part of the overall CBRS market. Neutral Host companies will deploy some Private LTE systems owned by the Enterprise. We consider these to be Private LTE networks. Other systems (in public buildings such as hotels or stadiums) will be owned by the Neutral Host, with coordination with Verizon/AT&T/T-Mobile to support multi-operator access. These are not included in the Private LTE totals.

For handset and IoT device forecasts, Mobile Experts interviewed multiple suppliers in the handset market to determine the maturity of RF filter technology and the software to support the unique restrictions of CBRS operation. Our direct interviews resulted in the delayed timing of the forecast reflected throughout this report.